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PARALLELOGRAM SHAPED OPENINGS IN PRESTRESSED CONCRETE TEE BEAMS

by

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies for acceptance, a thesis entitled "PARALLELOGRAM SHAPED OPENINGS IN PRESTRESSED CONCRETE TEE BEAMS", submitted by Eric P. LeBlanc in partial fulfilment of the requirements for the degree of Master of Science.

ABSTRACT

This investigation is the second in a program to study the behavior of and to develop design procedures for prestressed concrete tee beams containing large web openings. The test program was carried out in the Structural Engineering Laboratory of the University of Alberta under the supervision of Dr. J. Warwaruk*.

In this particular test series ten prestressed tee beams were tested, nine of which contained large web openings. The beams all had an overall depth of 20 inches, a flange width of 20 inches and a supported span of 20 feet.

The main test variables were: the shape of the large web openings, which were either rectangular or parallelogram shaped and the type of loading varying from seven point loading to two point loading. The other variables consisted of the prestressing force and the amount of shear reinforcement.

The data and results are presented in the form of tables, graphs and photographic plates.

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CHAPTER I

INTRODUCTION

In the construction of buildings of over one storey, a reduction in storey height will result in a saving on overall construction costs, proportional to the number of storeys composing the structure. A smaller storey height is possible, when using large prestressed concrete tee beams and girders, by passing heating and ventilating ducts through these, rather than under them as is so often done.

Efficient design of prestressed concrete tee beams with web openings, however, presents a problem which has not been investigated enough, up to the present time, to enable an engineer to design a series of such beams with confidence. Some research has been done in various countries on designing concrete beams containing transverse openings, but still much research is required to adequately comprehend the behavior of such beams.

In 1970, J. Sauve at the University of Alberta, conducted a series of tests on prestressed concrete tee beams containing rectangular web openings. The results of these tests, in addition to a small amount of work previously done in designing similar beams, formed the basis for the present test series.

Sauve's[8] tests were concerned with the effect of varying the vertical and longitudinal reinforcement of the beams, under different loading conditions and using rectangular openings.

The present test series at the University of Alberta, continues Sauve's work to investigate the behavior of, and to develop design

procedures for prestressed concrete tee beams containing large web openings. This particular series was concerned mainly, with varying the shape of the web openings from rectangular to parallelogram shape. Other variables were: the type of loading, the prestress force and the amount of shear reinforcing used.

Ten beams were tested and the behavior under load of each beam was recorded in the form of Demec strain gage readings over a section; deflection readings at the centerline and one third points; and readings of 77 electrical resistance strain gages mounted on the steel reinforcing bars. Numerous photographs were also taken of each test. However, the main concern was the observed behavior of the parallelogram type openings in the beams, as compared with the rectangular openings and no openings at all.

CHAPTER II

REVIEW OF PREVIOUS WORK

To enable concrete construction to keep pace with other types of construction, designers must be able to place openings transversely through their concrete beams, the same as holes are placed transversely through for example, steel beams. This will enable a flexibility in producing concrete construction products, which will result in greater competition to other materials industries and hopefully greater concrete use.

The concrete industry can profit from research along this line, however, up to the present time, only a limited amount of work has been done to investigate concrete beams having large web openings.

2.1 Prestressed Concrete Tee Beams with Large Web Openings

J. Sauve[8] conducted tests on nine prestressed concrete tee beams with rectangular web openings in the Structural Engineering Laboratory of the University of Alberta. This program, which is the basis for the present one, investigated nine 24 foot model beams tested under two point loads at various spacings. Other variables included: vertical shear reinforcing, as well as longitudinal reinforcing and supplementary lower web shear reinforcing.

Some observations and conclusions from this program were:

a) Prestressed concrete tee beams containing large web openings, cannot be designed for flexure using the ACI Code's minimum shear reinforcement conditions, even though the actual ultimate shear capacity

obtained, could far exceed that designed for flexure.

b) Any additional shear reinforcement provided, served to increase the load carrying capacity of a beam containing large web openings, by an amount ranging from 15% to 22%.

c) Additional shear reinforcement, also, confined failure to a location where there was an abrupt change in cross-sectional area of concrete.

d) An extra amount of vertical reinforcement, placed in the posts, gave these posts the capacity required to cause a localizing of the failure in the lower web, if this web had no vertical reinforcement. However, a minimum amount of inclined shear reinforcement, placed in the lower web, caused the failure to be localized in the posts.

e) The addition of both post and lower web reinforcement resulted in a redistribution of stresses in the shear span such that all sections were more equally stressed in diagonal tension.

f) A considerable increase in supplementary longitudinal reinforcement did not significantly increase the shear capacity of the beams.

g) A decrease in the number of openings in the shear span increased considerably the shear capacity of the beams.

2.2 Prestressed Tee Beams with Large Web Openings

Ragan and Warwaruk[7] tested 6 prestressed tee beams containing web openings at the University of Alberta. In this program, four model

beams were tested in the Structural Engineering Laboratory and two full size beams were tested in the field. The design of the two full size beams was based on the results obtained from the model beams.

Some of their observations and conclusions are:

In the model beams:

a) Cracking extended vertically downward from approximately the center point of the web openings; hence it was concluded in the full size beams, to distribute the prestressing strands almost evenly across the vertical section of the lower web.

b) Severe cracking at the connection of the "post" and flange led to the provision of steel in the posts at 1.3% of the horizontal area of these posts.

c) All failures were due to inclined cracking in the lower web and always in the half span which had the least amount of web reinforcement; hence, the full size beams were provided with U stirrups in the lower web spaced at 6 to 12 inches.

d) The mode of failure of all beams with openings was by the formation of mechanisms. None of the beams, neither model nor full size failed in a flexural manner.

2.3 Reinforced Concrete Tee Beams with a Web Opening

Lorentsen[4], of the Royal Institute of Technology in Stockholm, conducted analytical and experimental research on reinforced concrete girders having a single web opening. Four beams were tested under different loading conditions.

His tests confirmed, in general, the behavior pattern predicted by the elastic theory and also showed that there was a reserve of capacity available, due to the redistribution of moments, between the stressed sections located at the edges of the opening. Lorentsen also showed that for statically loaded structures, satisfactory structural capacity can be achieved if the sections near a hole are designed to resist the normal and bending forces. He pointed out that in simply supported beams, there are two quantities which make the location of a hole near the midspan desirable:

i) the magnitude of the flange moment

ii) the shear force.

In simply supported beams, the flange moment is small near a support and the shear force is large. The combination of these two quantities, yields high principal tensile stresses in the concrete in regions away from the midspan.

An important conclusion which he made is that, in the region of a hole, the members should be overdesigned with respect to the crushing of the concrete. This guards against the occurrence of a plastic condition at working loads. This condition is not desirable, since the moment may change in sign in this region, depending on the position of the load. He also concludes that the principles presented can be applied to cases where more than one hole exists.

2.4 Rectangular Reinforced Concrete Beams with Large Web Openings

Nasser, Acavalos and Daniel[6] of the University of Saskatchewan,

tested 9 rectangular beams containing web openings. They were able to verify that large openings behave similar to a Vierendeel panel, that contraflexure points exist at the approximate midspan of the cross members, that the diagonal force concentration at the corners of an opening is twice the simple shear force, and that adequately reinforced large openings do not reduce the ultimate capacity of a beam, but reduce the stiffness and hence increase deflections.

CHAPTER III

RESEARCH PROGRAM

This test series is the second in a program to investigate the behavior of and to develop design procedures for prestressed concrete tee beams containing large web openings. This series is concerned with the study of the overall behavior of such members and particularly with the effect of varying the shape of openings from rectangular to parallelogram shaped, and also of varying the type of loading.

Ten prestressed concrete tee beams were tested. All beams were 24 feet long with a supported span of 20 feet. The flange width for all beams was 20 inches and the overall depth was 20 inches. The first beam was the control beam and contained no web openings, while the other nine beams contained eight openings except for Beam 6* which contained six openings. The parallelogram shaped openings had a total area of 878 in^2 while the rectangular openings had a total area of 996 in^2 for eight holes and 747 in^2 for six holes. In all cases the width of the posts between holes, measured horizontally, was 8 inches. Along with varying the shape of opening, the other predesignated variables were: the loading, which varied from seven point loading spaced at 2 feet centers to two point loading spaced at 8 and 12 feet centers; the prestressing force; and, the vertical and inclined shear reinforcement as well as supplementary inclined shear stirrups in the lower web.

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* The end holes in Beam 6 were filled with concrete to try and shift the shear failure to the second opening from the outside.

Table 3.1 summarizes the shear reinforcement details for each beam of this series. Beam sections, reinforcement details, hole arrangement and load positions are shown in Figures 3.1, 3.2(a) and (b), 3.3, and 3.4 respectively. In all cases the web openings were located so that the applied point loads, shown in Figure 3.3, passed through the midpoint of the post at the tops of the openings. The effective prestress force developed by the 4 and 5-3/8 inch, 7 wire strands and the concrete strength were not variables, although small variations in these did occur.

The inclined and vertical shear reinforcement used throughout the fabrication of the beams consisted of #3 stirrups, prebent to a specified shape by the supplier.

The longitudinal reinforcement consisted of #3 deformed reinforcing bars. The steel in the control beam was designed in accordance with ACI standard (318-63 & 71)[1,2], (see Appendix C for further details).

The prestressing operation was carried out between 2 prestressing abutments spaced at 25 feet. Slip type formwork was used in the concreting operation; these included styrofoam blocks for shaping the openings.

All beams were cast using High Early Strength Cement. The prestressing strands of all of the 10 beams were cut after six days of moist curing. Following the release of prestress, the beams were stored in the laboratory atmosphere for varying periods prior to testing. Testing took place at times varying from 21 to 29 days after casting. Concrete test cylinders were molded from the batch mixes used and were tested for compressive strength and tensile splitting

strength on the same day as the beams.

All ten beams were instrumented in the same fashion. The instrumentation consisted of electrical resistance strain gages, mounted on the shear and longitudinal reinforcement at critical points, survey level readings at the centerline and the one-third points for deflection measurements, and Demec points fixed to the concrete at the centerline for strain distribution measurements. Electrical resistance strain gages were waterproofed by applying an epoxy type paint cover. Level readings were taken off scales, graduated to 0.01 inches, which were suspended from the lower portion of the beam. The primary use of the Demec points was for the measurement of initial shortenings and time losses. In addition, the strain readings between the Demec points were taken throughout the actual testing. Figure 3.6 shows typical instrumentation details.

Steel beam seats were used to seat the beams during the tests. These seats were fitted on the beams at the support points and were clamped in place; Figure 3.5 depicts a typical beam seat.

The beams were loaded by jacks mounted on a harness. The upper part of the harness lay over the beam and the lower part, under the loading floor, was pushed on by the jack, which was placed between the floor and the lower part of the harness as shown in Figure 3.7. Seven of these were used in three tests and two were used in the remaining seven tests. The jacks were hooked up to a manifold which allowed them to exert equal point loads on the longitudinal centerline of the top flange. In each case, the jacking force was applied over the posts. Figure 3.3 shows the different load positions and Figure

3.4 shows the loading positions for particular beams. A steel plate was placed under the top part of the loading harness so as to keep the load from the jack concentrated at the longitudinal centerline of the beam. An overall view of the test set-up is shown in Figure A.4. Figure 3.7 illustrates a typical test set-up and Figure A.6 illustrates a typical loading harness cross-section.

Sufficient load increments were applied in order that the behavior could be well recorded. For the seven point loading, increments of 500 lb. were used up to cracking and 250 lb. from cracking to failure. For the two point loading, increments of 1000 to 2000 lb. were used up to cracking and 500 to 250 lb. used from cracking to failure. A total of at least 20 increments was obtained in each test. At the end of each increment, readings were taken of the electrical resistance strain gages, of the deflections and of the Demec points. All visible cracking was observed and recorded on the surface of the concrete. To provide a good record of cracking behavior, photographs were taken before and after failure.

BEAM NO.	STIRRUP SPACING (IN)	AREA PER STIRRUP (IN^2)	EQUIVALENT STIRRUPS PER POST	LONGI. REINFORCEMENT LOWER WEB (IN^2)	LONGI. REINFORCEMENT UPPER WEB (IN^2)	SUPPL. REINF. LOWER WEB	LOADING	OPENING
1	15	.22	-	.22	.66	NO	7 @ 2'c/c	NO OPENING
2	8	.22	3	.22	.66	NO	2 @ 8'c/c	INCLINED
3	5	.22	4	.22	.66	NO	2 @ 12'c/c	INCLINED
4	5	.22	4	.22	.66	YES	2 @ 8'c/c	INCLINED
5	8	.22	3	.22	.66	NO	2 @ 8'c/c	RECTANGULAR
6	5	.22	4	.22	.66	NO	2 @ 8'c/c	RECTANGULAR
7	5	.22	4	.22	.66	YES	2 @ 8'c/c	RECTANGULAR
8	5	.22	4	.22	.66	YES	7 @ 2'c/c	INCLINED
9	12	.22	2	.22	.66	NO	2 @ 8'c/c	INCLINED
10	12	.22	2	.22	.66	YES	7 @ 2'c/c	INCLINED

TABLE 3.1 BEAM REINFORCEMENT DETAILS

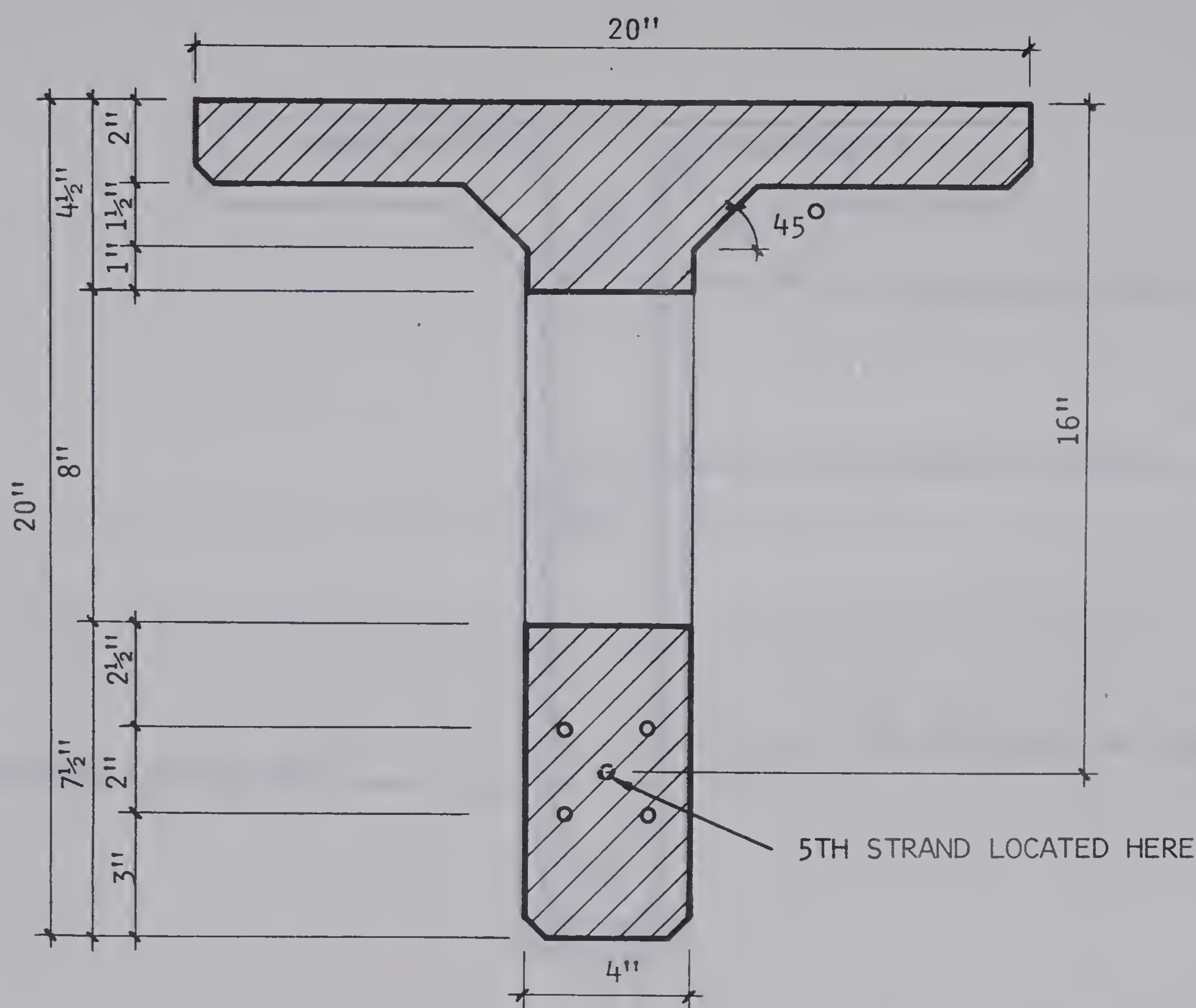
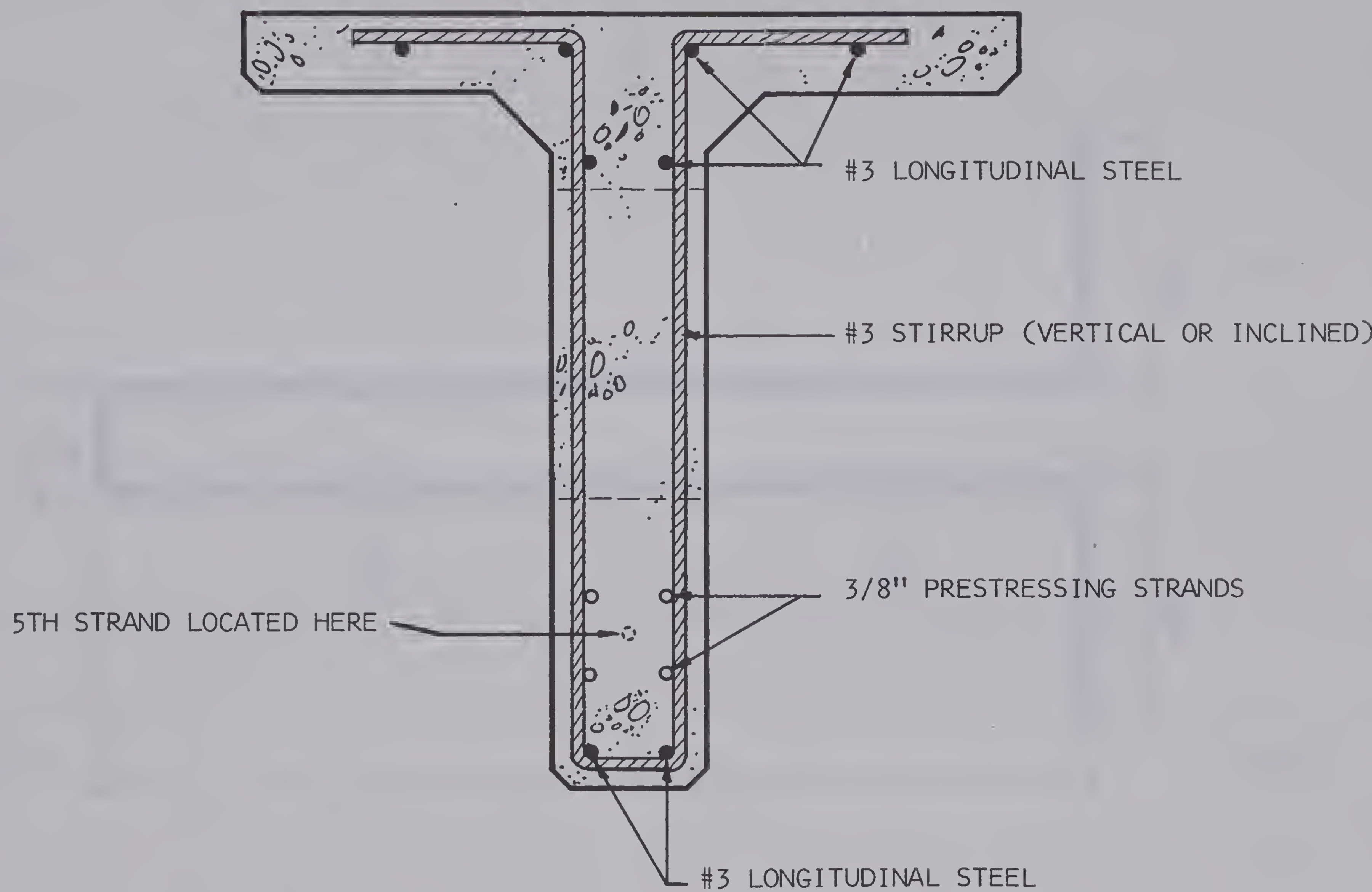
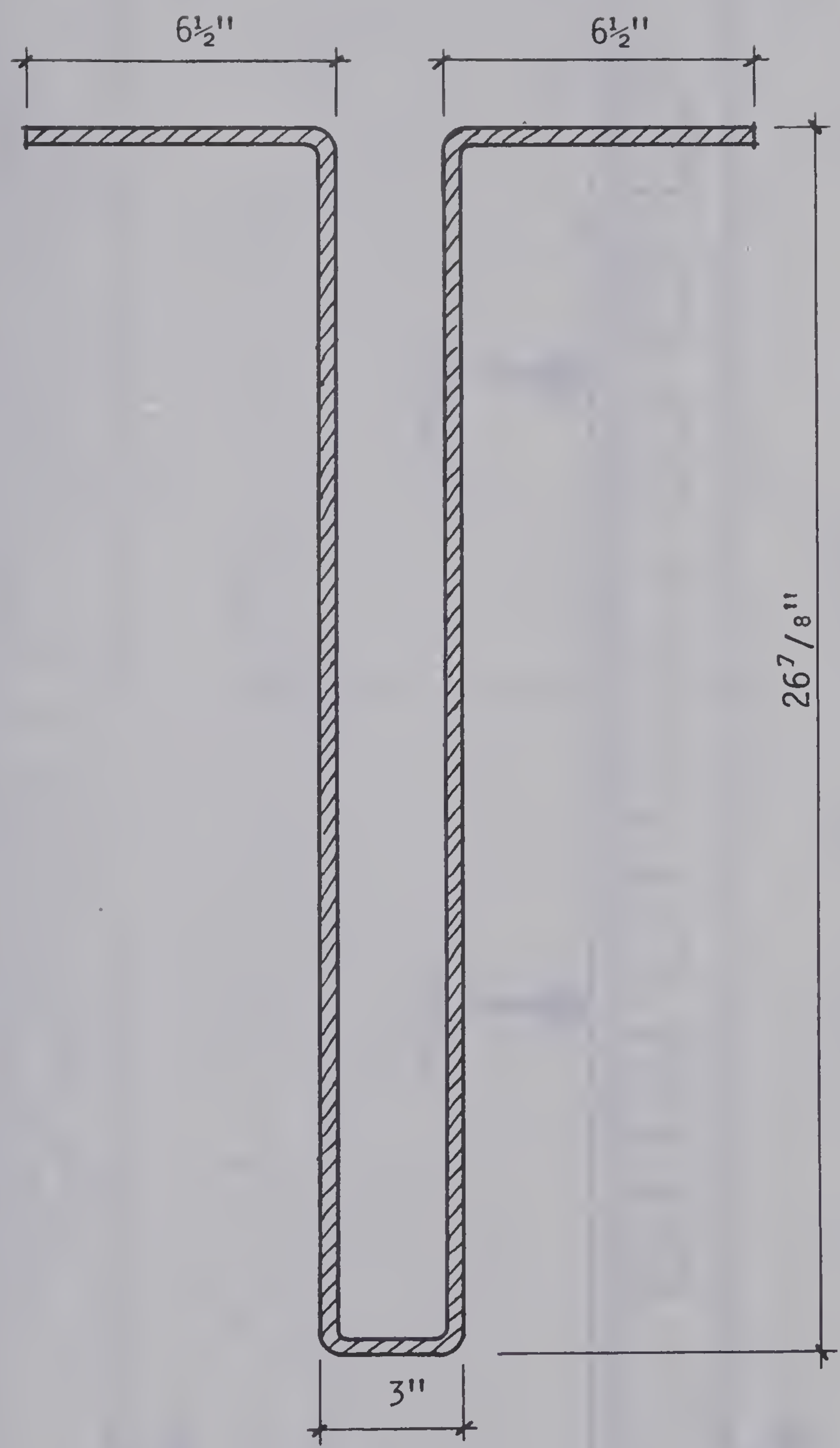


FIGURE 3.1 TYPICAL CONCRETE X-SECTION AT AN OPENING



NOTE: 1/2 INCH CONCRETE COVER PROVIDED FOR STIRRUPS

FIGURE 3.2(a) TYPICAL BEAM REINFORCEMENT DETAIL



NOTE: These stirrups were inclined at 45° to the hortizontal

FIGURE 3.2(b) DETAIL OF INCLINED STIRRUP

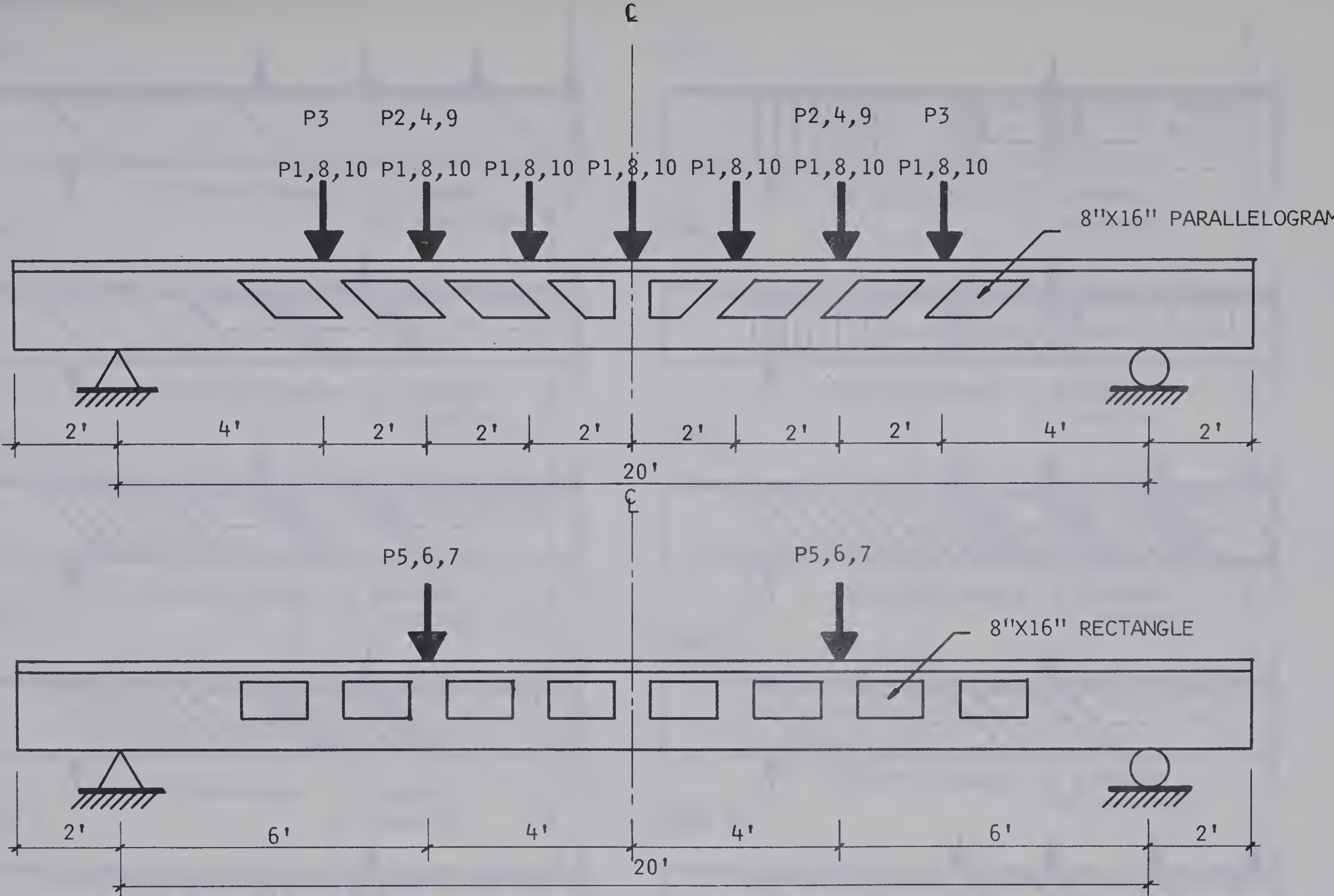
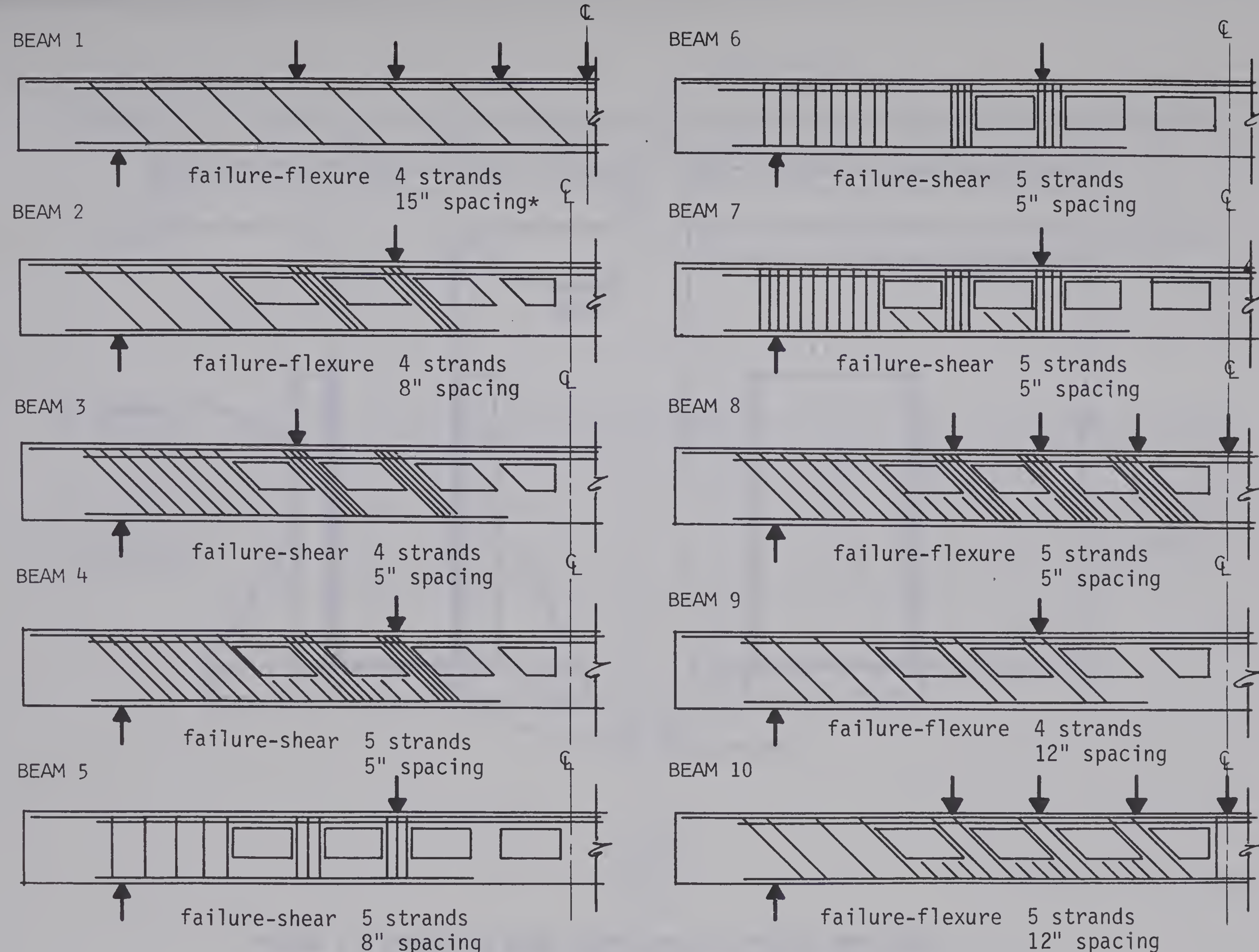


FIGURE 3.3 HOLE ARRANGEMENT AND LOAD POSITIONS



*stirrup spacings shown refer to those in the solid shear span

FIGURE 3.4 TEST BEAMS AND REINFORCEMENT DETAILS

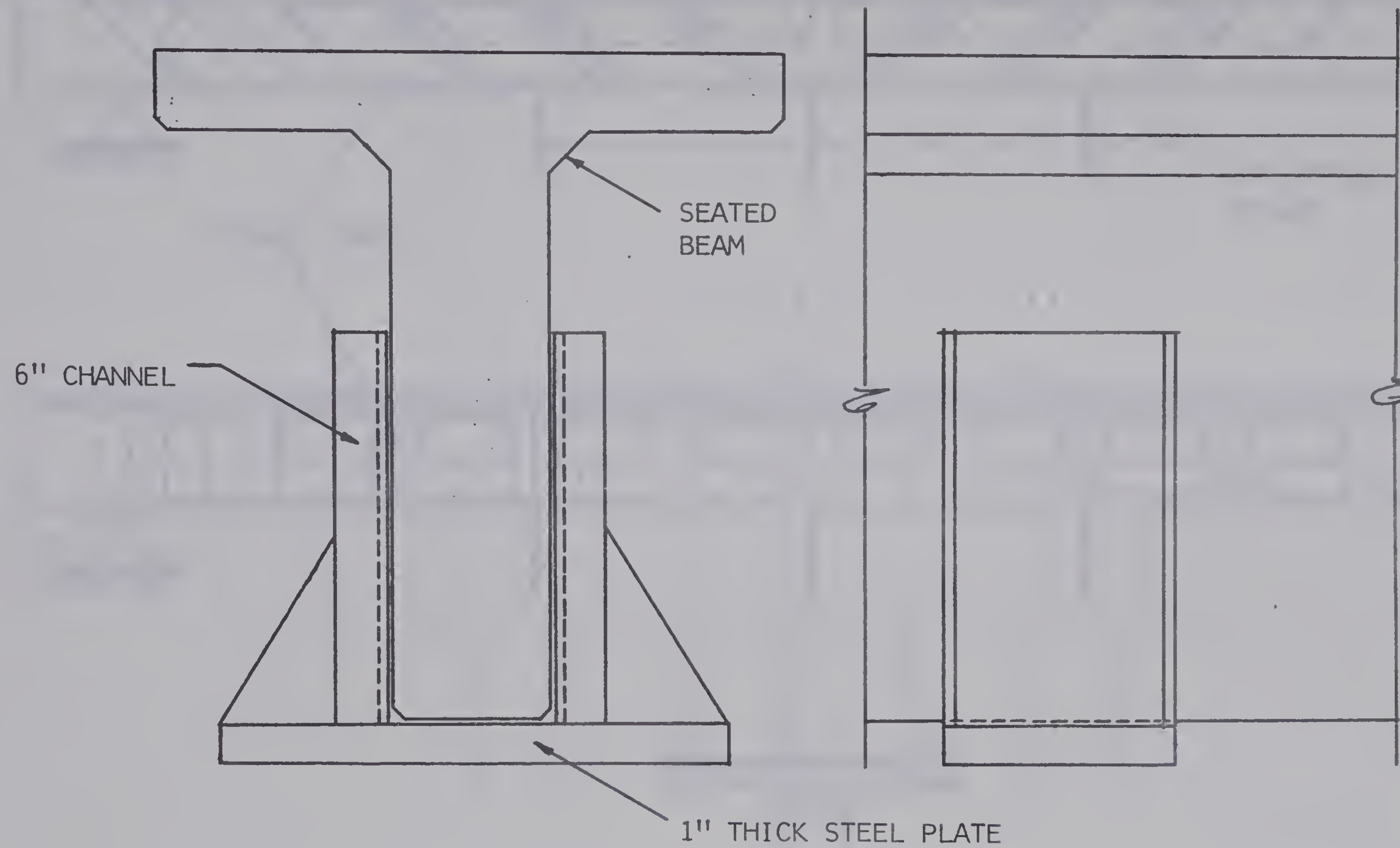


FIGURE 3.5 FRONT AND SIDE ELEVATIONS OF TYPICAL BEAM SEAT

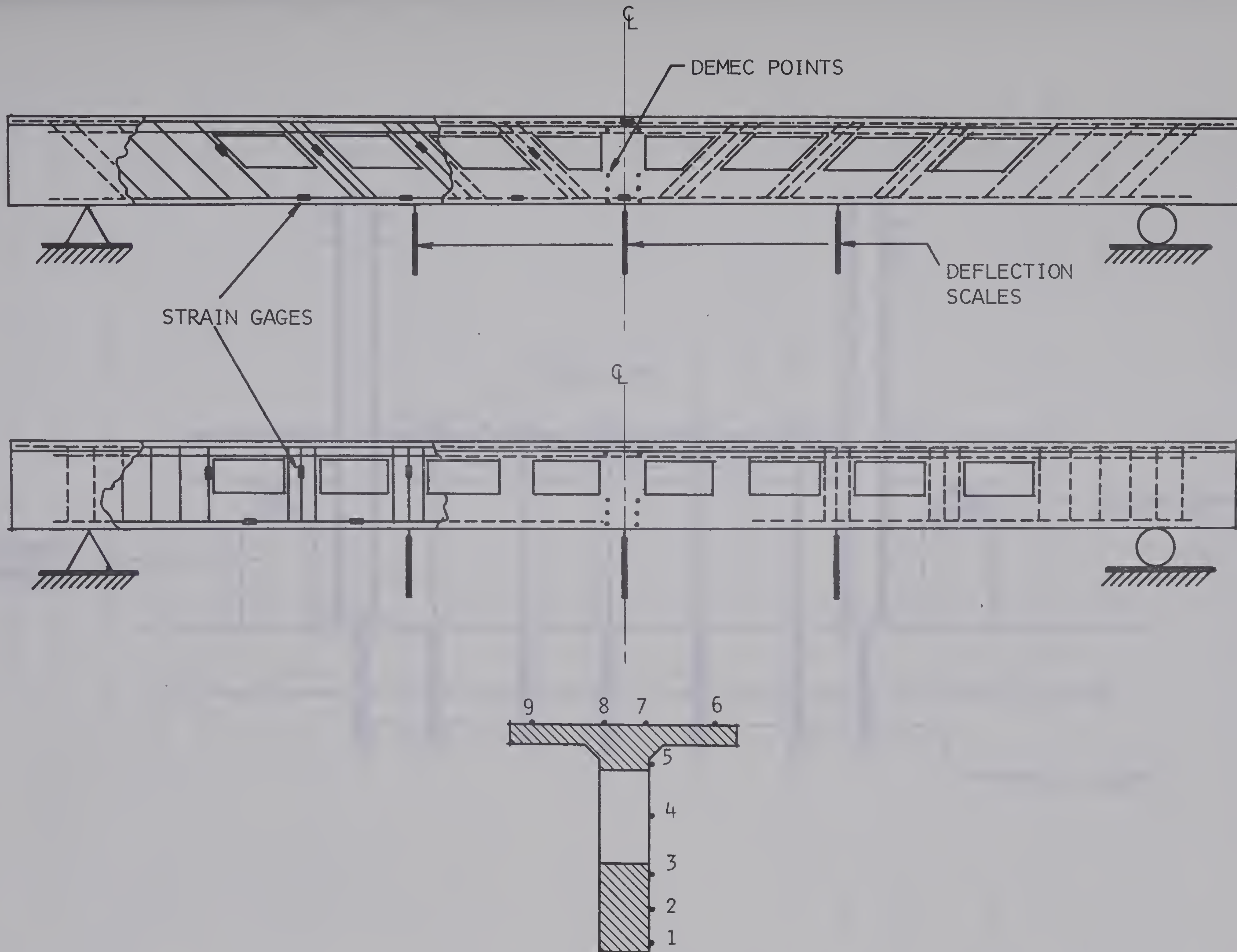


FIGURE 3.6 BEAM INSTRUMENTATION DETAILS AND LOCATIONS

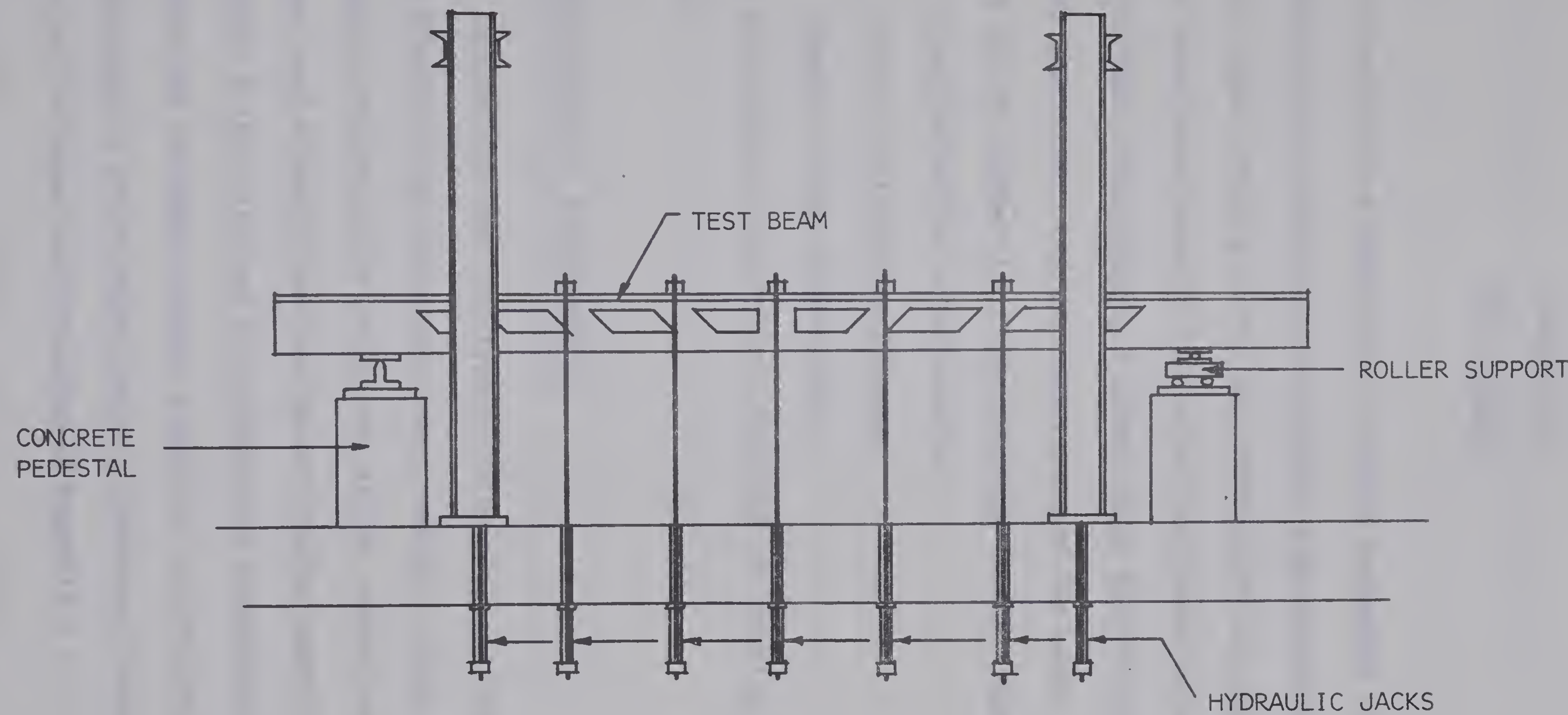


FIGURE 3.7 TYPICAL TEST SET-UP

CHAPTER IV

TEST RESULTS

The graphical and photographic results presented in this chapter, were obtained both directly and indirectly from measurements taken during the actual testing of the ten prestressed tee beams. The measurements taken were those of electrical resistance strain gages, mechanical Demec strain gages, a survey level and the Amsler hydraulic loading apparatus. The instrumentation of the beams is depicted in Figure 3.6 of Chapter III. The graphical results consist of:

1) Load deflection relationships
2) Strain distribution diagrams
3) Moment strain relationships

The photographic results are comprised of cracking and failure patterns.

4.1 Load-Deflection Relationships

The deflections used in Figures 4.1(a), (b) and (c) were those obtained directly from the survey level readings. Beam deflections were taken at the one-third points and at the centerline. Applied loads were read directly from the Amsler loading apparatus scale.

Figures 4.1(a), (b) and (c) present the load-centerline deflection curves for the beams grouped according to load group 1, load group 2 and load group 3 and 4 respectively. Individual load-deflection diagrams for the beams are presented in Appendix B.

4.2 Strain Distribution over the Depth of Section

The strains, over the depth of the beam at midspan, depicted in this section, were those resulting from the change in length between the Demec points mounted on the test specimens. The readings were taken at those points shown in the instrumentation diagram, Figure 3.6. Strains were plotted versus depth for particular load values for each beam. The plots for each beam were in turn grouped according to the type of loading and each plot can be related to that of the control beam in group 1. Figure 4.2(a) shows those relationships for beams of load group 1, Figure 4.2(b) for those of group 2 and Figure 4.2(c) shows those relationships for beams of load group 3 and 4. The last strain diagram for most beams are those of the beams penultimate load.

4.3 Moment-Reinforcement Strain Relationships

The reinforcement strains were measured directly from the electrical resistance strain gages mounted on the supplementary reinforcing bars. Locations of the gages for particular beams are presented in Appendix B, along with the direct readings. A total of 77 of these strain gages were used in this test series. Center span moment values computed from the applied loads were used for plotting purposes.

Figure 4.3 shows the general locations of the strain gages for all ten beams, and associates a label with each location. The location of each of these gage points, with respect to the web openings, is shown on the beam details in Appendix B. The moment versus strain plots following this figure, are shown in Figures 4.4(a) to 4.4(k) and

give the plot of strain at each gage for each beam with a gage at the locations shown on Figure 4.3. The behavior of the reinforcing for each beam at each of these locations can thus be easily compared.

4.4 Illustrative Cracking and Failure Results

This section consists of photographic plates of the cracking and failure patterns of Beams 1 to 10 inclusive. These are found in Figures 4.5(a) to (j).

4.5 Summary of Test Results

Table 4.1 presents a summary of test results.

4.6 Summary of Results Compared with Theoretical Values

Table 4.2(a) presents the theoretical ultimate moment and load according to the ACI Code[1] using fsu = 243.75 ksi for the 4 strand beams and fsu = 242.5 ksi for the 5 strand beams, compared with the actual ultimate values of load and moment obtained from the tests.

Table 4.2(b) presents the theoretical ultimate moment and load according to the ACI Code using fsu = 275 ksi, (actual ultimate stress of the 3/8 inch strands at fracture) compared with the actual ultimate values of load and moment obtained from the tests, for the particular beams that failed in the flexural mode i.e. the strands ruptured. The theoretical ultimate moment capacity of the beams is computed in Appendix C.

BEAM NO.	LOADING	FAILURE LOAD (KIPS)	FAILURE MOMENT (IN-KIPS)	TYPE OF FAILURE	TYPE OF OPENING	NO. OF STRANDS	STIRRUP SPACING (IN)	STIRRUPS PER POST	fi (psi)
1	7 @ 2'c/c	6.4	1766	FLEXURE	NO OPENINGS	4	15	-	5215
2	2 @ 8'c/c	19.5	1404	FLEXURE	INCLINED	4	8	3	5234
3	2 @ 12'c/c	23.0	1104	SHEAR	INCLINED	4	5	4	5325
4	2 @ 8'c/c	23.5	1692	SHEAR	INCLINED	5	5	4	5302
5	2 @ 8'c/c	17.25	1242	SHEAR	RECTANGULAR	5	8	3	5118
6	2 @ 8'c/c	18.75	1350	SHEAR	RECTANGULAR	5	5	4	4977
7	2 @ 8'c/c	18.5	1332	SHEAR	RECTANGULAR	5	5	4	5001
8	7 @ 2'c/c	8.25	2277	FLEXURE	INCLINED	5	5	4	5086
9	2 @ 8'c/c	20.25	1458	FLEXURE	INCLINED	4	12	2	5298
10	7 @ 2'c/c	7.5	2070	FLEXURE	INCLINED	5	12	2	5771

TABLE 4.1 A SUMMARY OF TEST RESULTS

BEAM NO.	LOADING	THEORETICAL FAILURE MOMENT* (IN-KIPS)	LOAD (KIPS)	ACTUAL FAILURE MOMENT (IN-KIPS)	LOAD (KIPS)	STRANDS	TYPE OF FAILURE
1	7 @ 2'c/c	1140	4.13	1766.4	6.4	4	FLEXURE
2	2 @ 8'c/c	1140	15.85	1404.0	19.5	4	FLEXURE
3	2 @ 12'c/c	1140	23.75	1104.0	23.0	4	SHEAR
4	2 @ 8'c/c	1427	19.82	1692.0	23.5	5	SHEAR
5	2 @ 8'c/c	1427	19.82	1242.0	17.25	5	SHEAR
6	2 @ 8'c/c	1427	19.82	1350.0	18.75	5	SHEAR
7	2 @ 8'c/c	1427	19.82	1332.0	18.5	5	SHEAR
8	7 @ 2'c/c	1427	5.17	2277.0	8.25	5	FLEXURE
9	2 @ 8'c/c	1140	15.82	1458.0	20.25	4	FLEXURE
10	7 @ 2'c/c	1427	5.17	2070.0	7.5	5	FLEXURE

* fsu = 243.75 ksi 4 Strand Beams; fsu = 242.5 ksi 5 Strand Beams

TABLE 4.2(a) COMPARISON OF ACI CODE THEORETICAL FAILURE LOAD AND MOMENT TO ACTUAL VALUES

BEAM NO.	LOADING	THEORETICAL MOMENT (IN-KIPS)	THEORETICAL LOAD (KIPS)	ACTUAL FAILURE MOMENT (IN-KIPS)	ACTUAL FAILURE LOAD (KIPS)	STRANDS
1	7 @ 2'c/c	1295	4.7	1766.4	6.4	4
2	2 @ 8'c/c	1295	18.0	1404.0	19.5	4
8	7 @ 2'c/c	1627	5.9	2277.0	8.25	5
9	2 @ 8'c/c	1295	18.0	1458.0	20.25	4
10	7 @ 2'c/c	1627	5.9	2070.0	7.5	5

TABLE 4.2(b) THEORETICAL ULTIMATE MOMENT AND LOAD OF FLEXURAL FAILURES USING fsu = 275 ksi

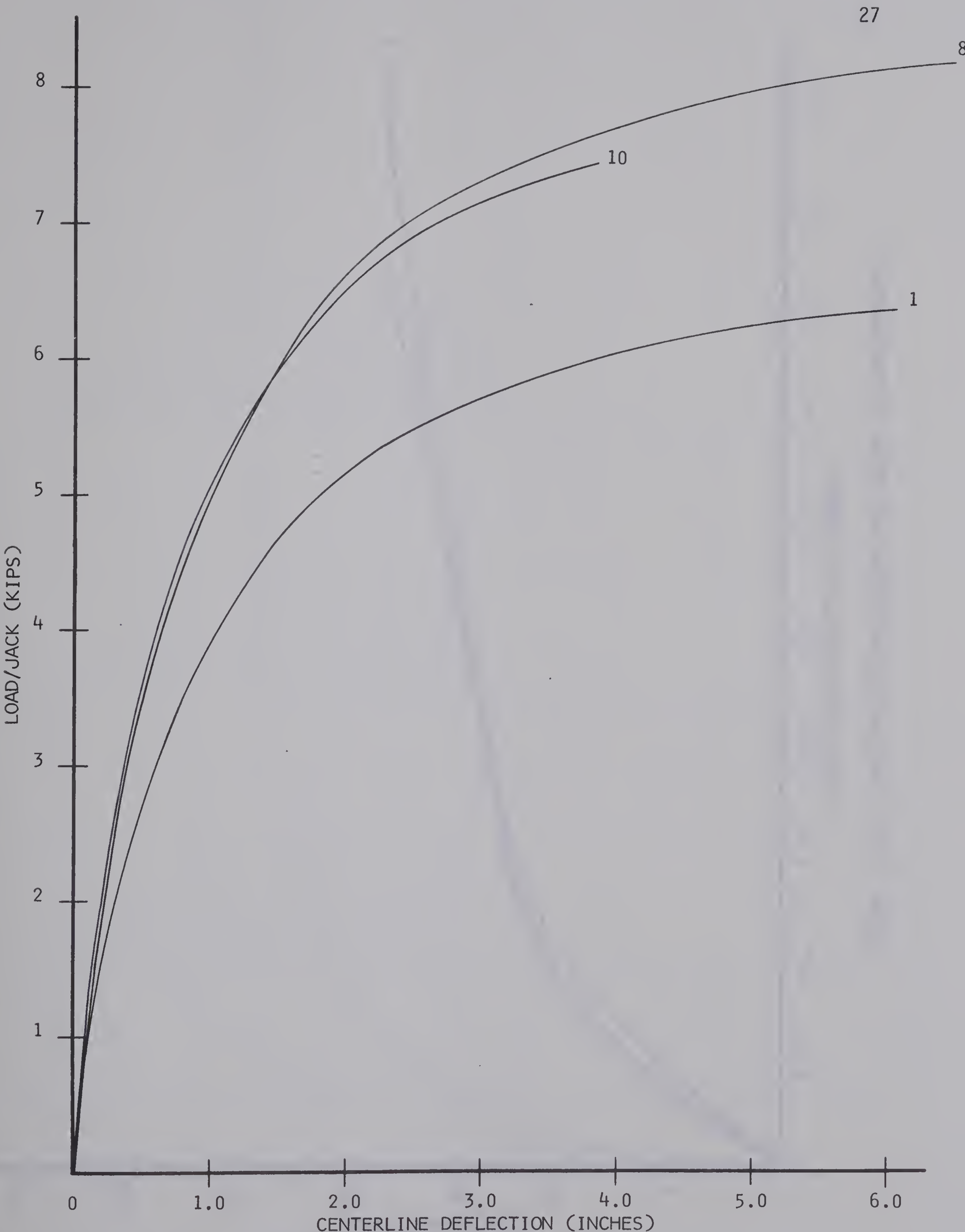
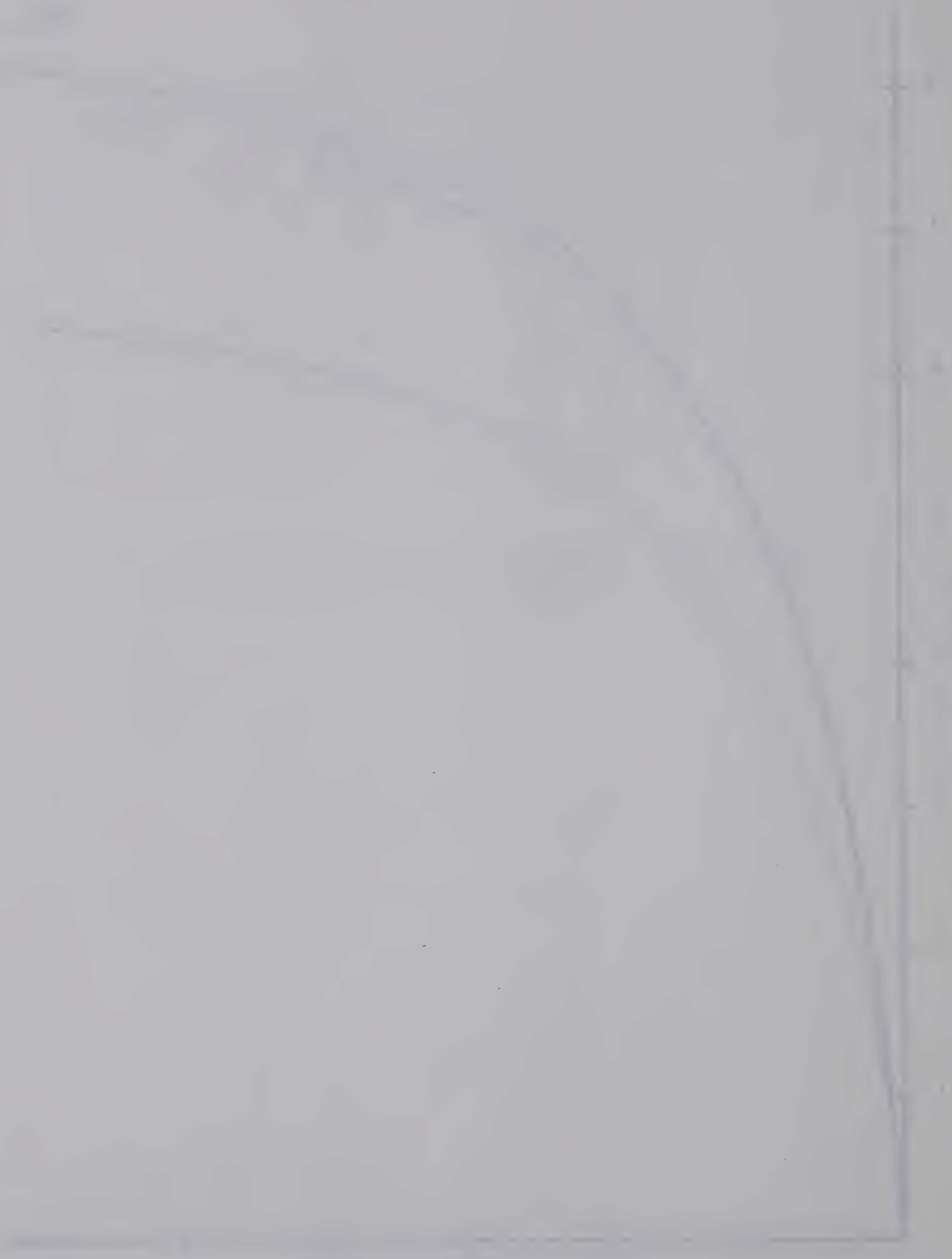


FIGURE 4.1(a) LOAD-DEFLECTION DIAGRAM FOR BEAMS OF LOAD GROUP 1



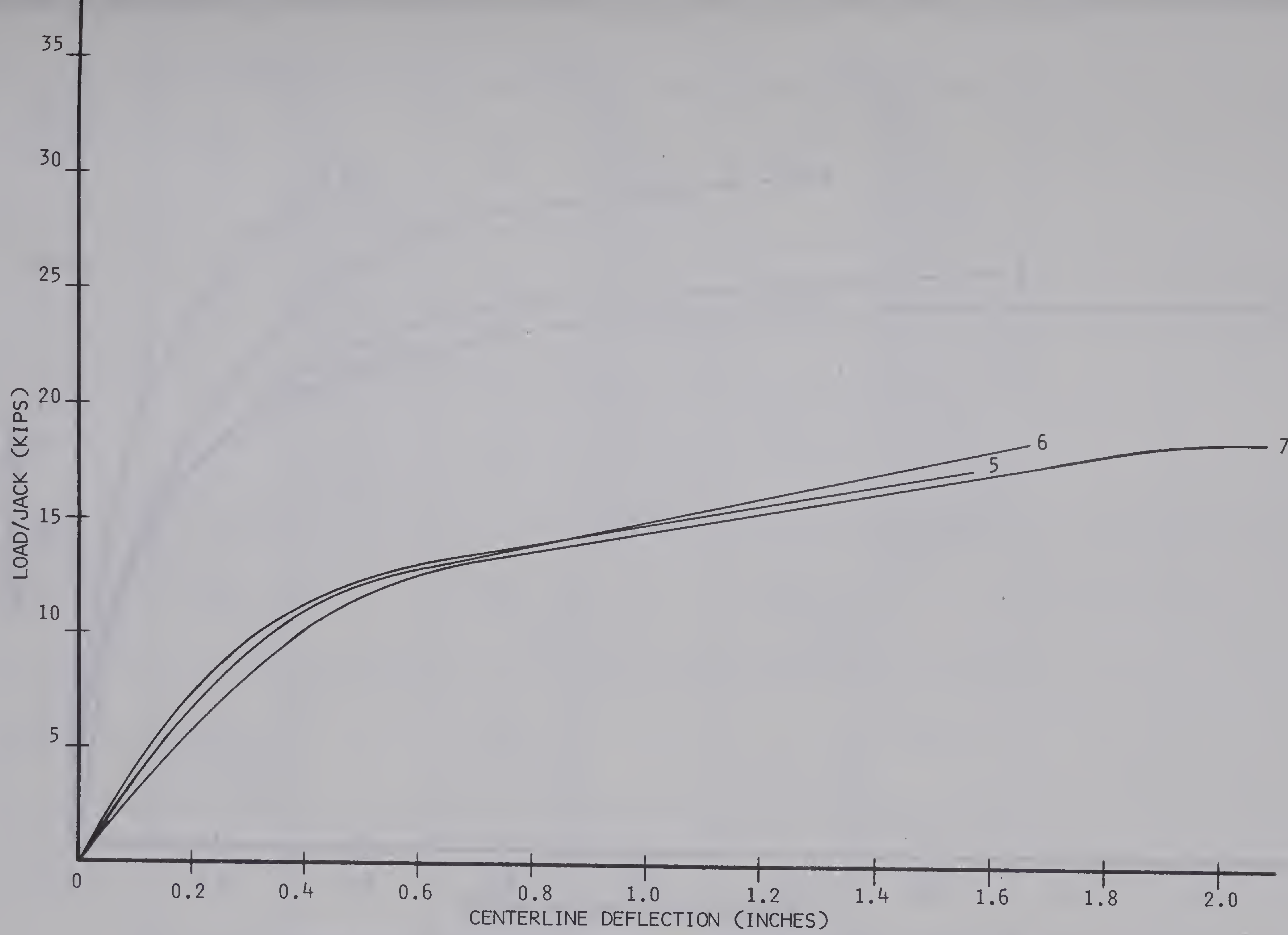


FIGURE 4.1(b) LOAD-DEFLECTION DIAGRAM FOR BEAMS OF LOAD GROUP 2

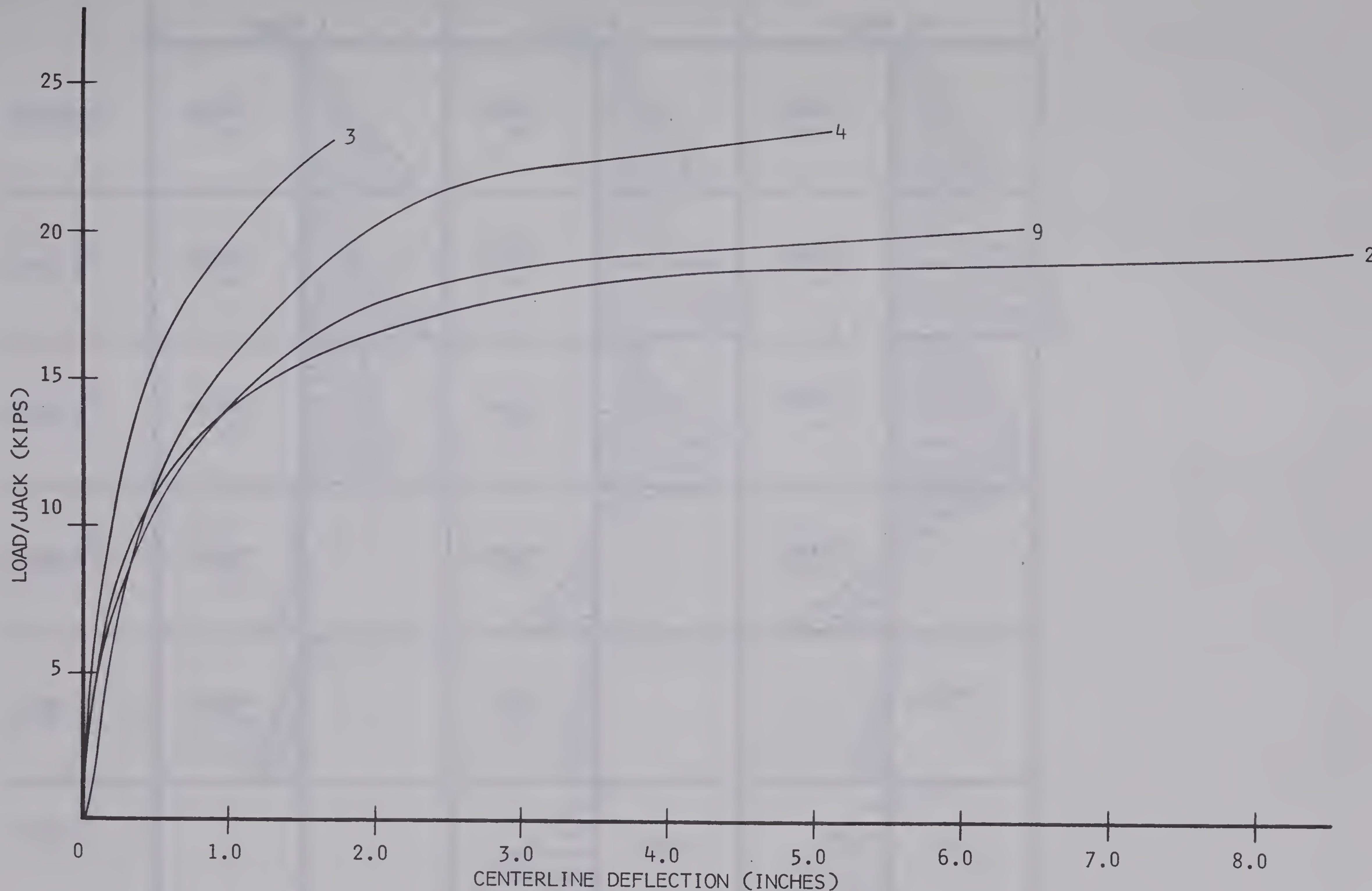


FIGURE 4.1(c) LOAD-DEFLECTION DIAGRAM FOR BEAMS OF LOAD GROUPS 3 & 4

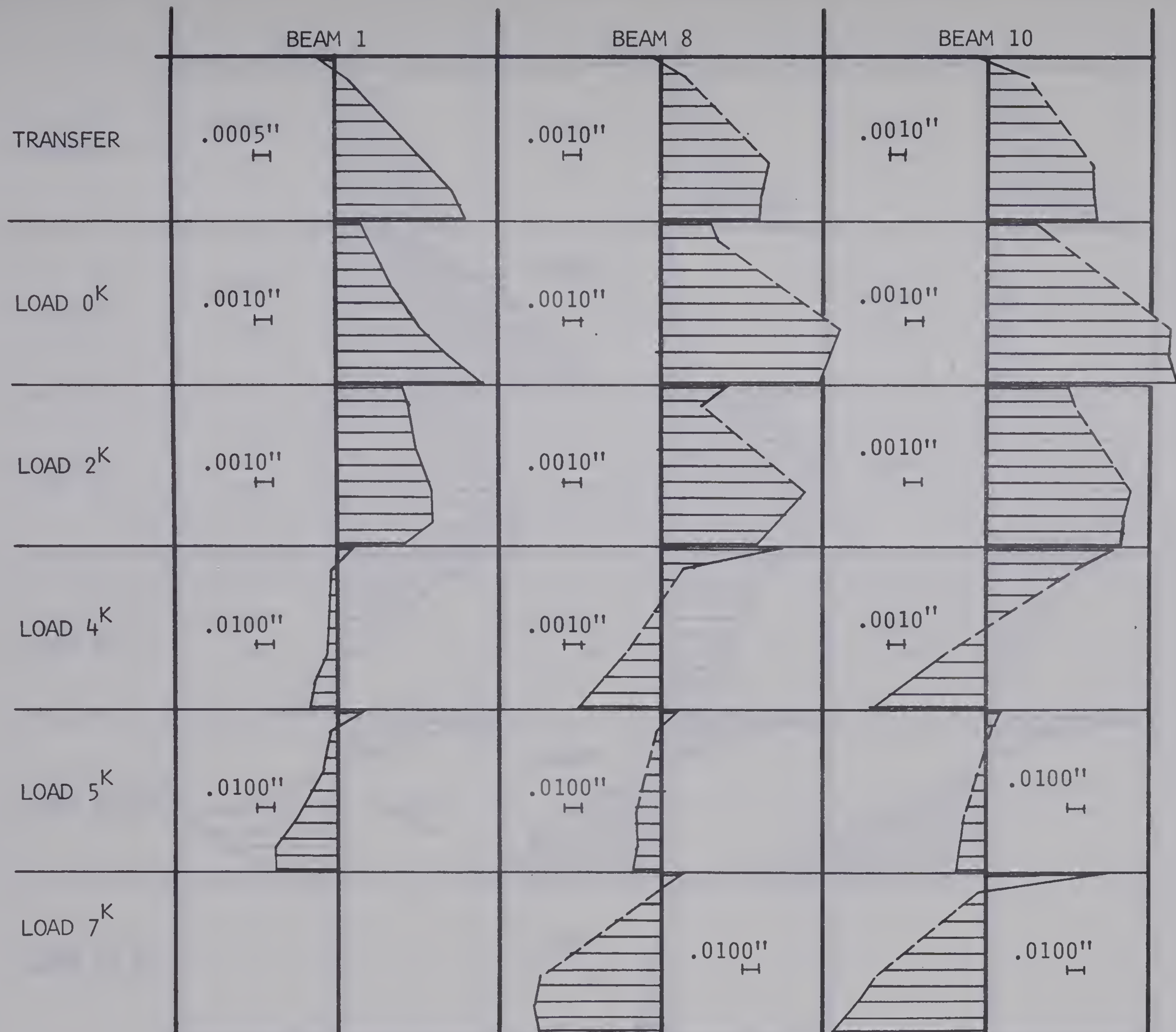


FIGURE 4.2(a) STRAIN DISTRIBUTION AT ℄ FOR BEAMS OF LOAD GROUP 1

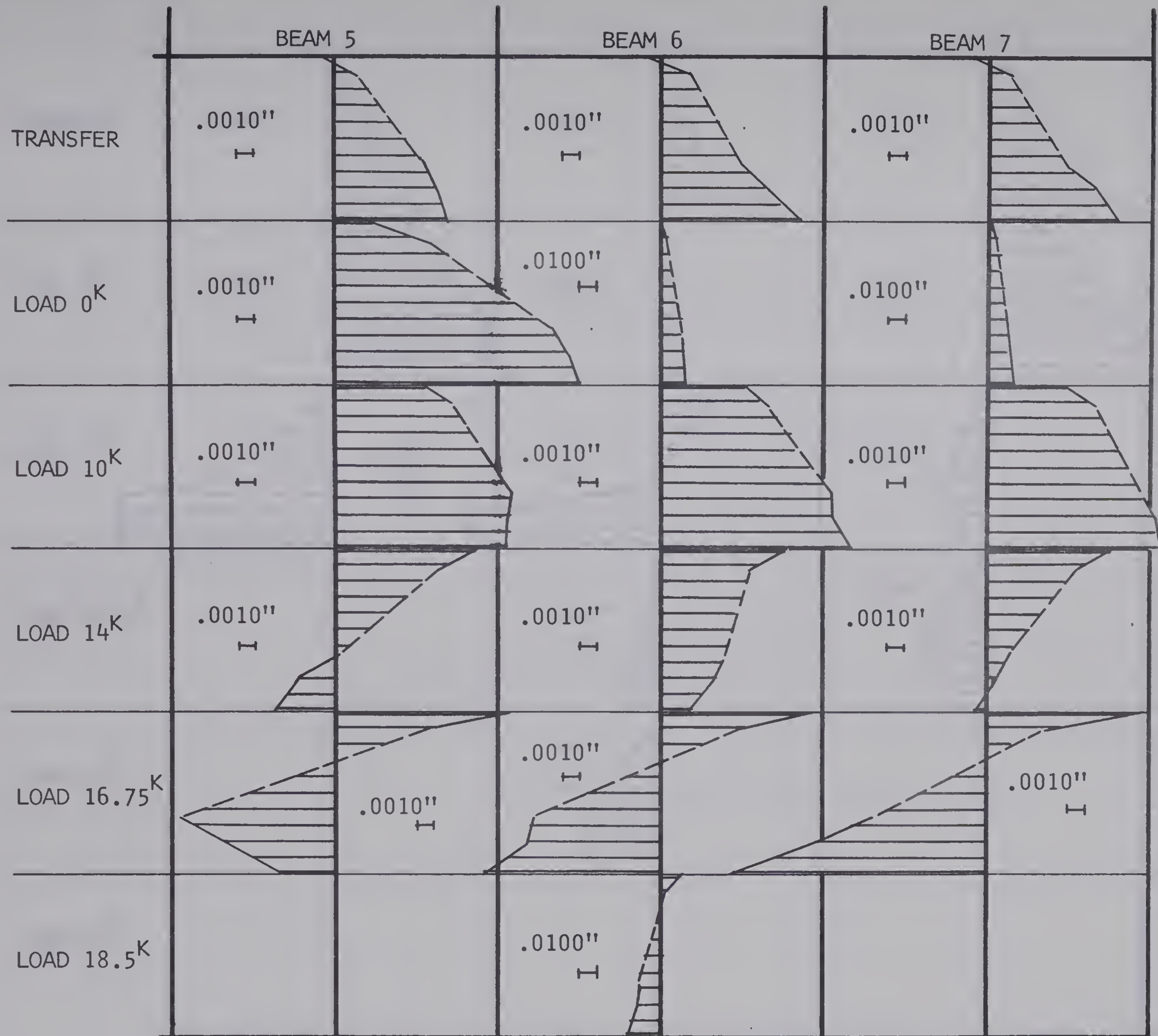


FIGURE 4.2(b) STRAIN DISTRIBUTION AT ℄ FOR BEAMS OF LOAD GROUP 2

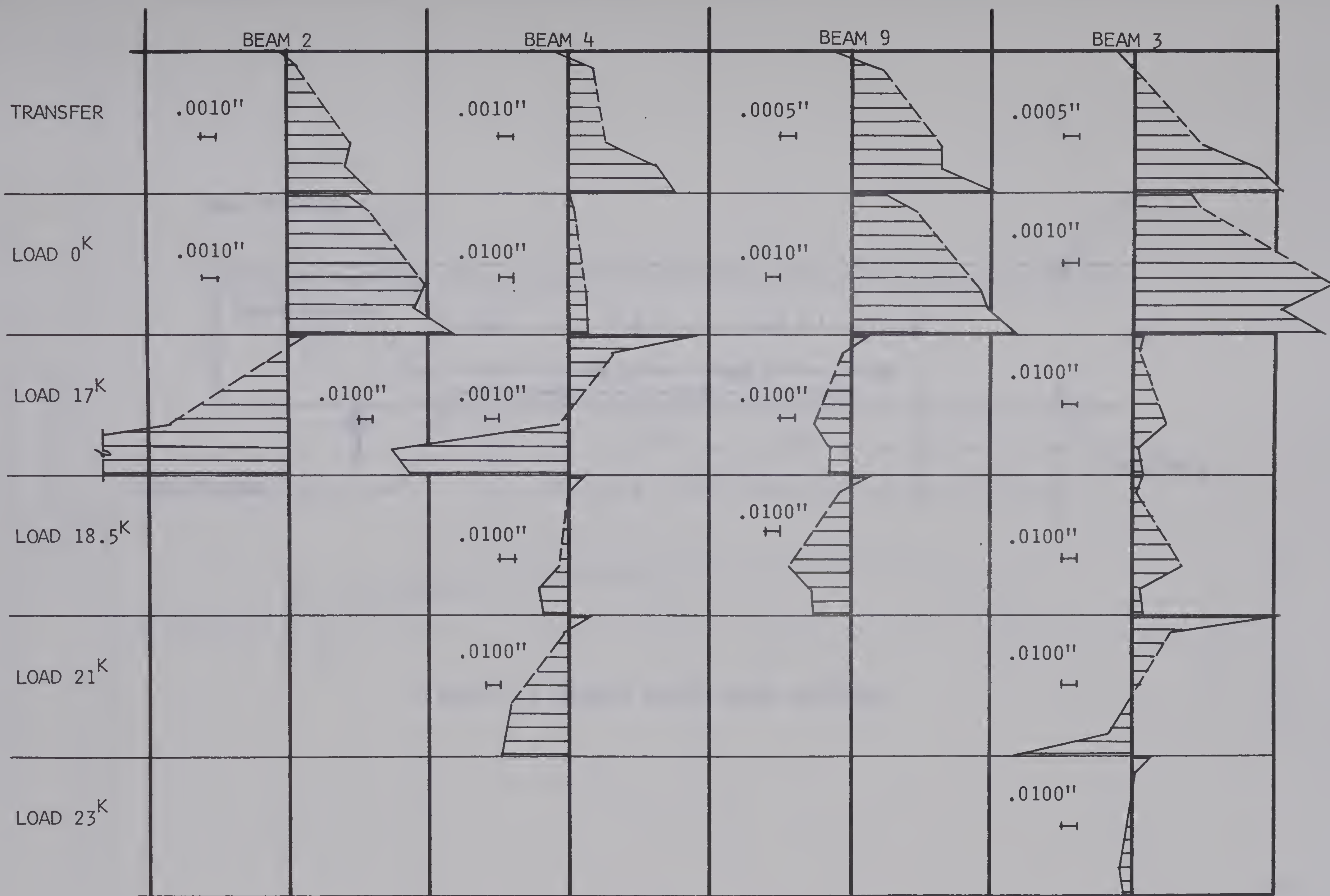
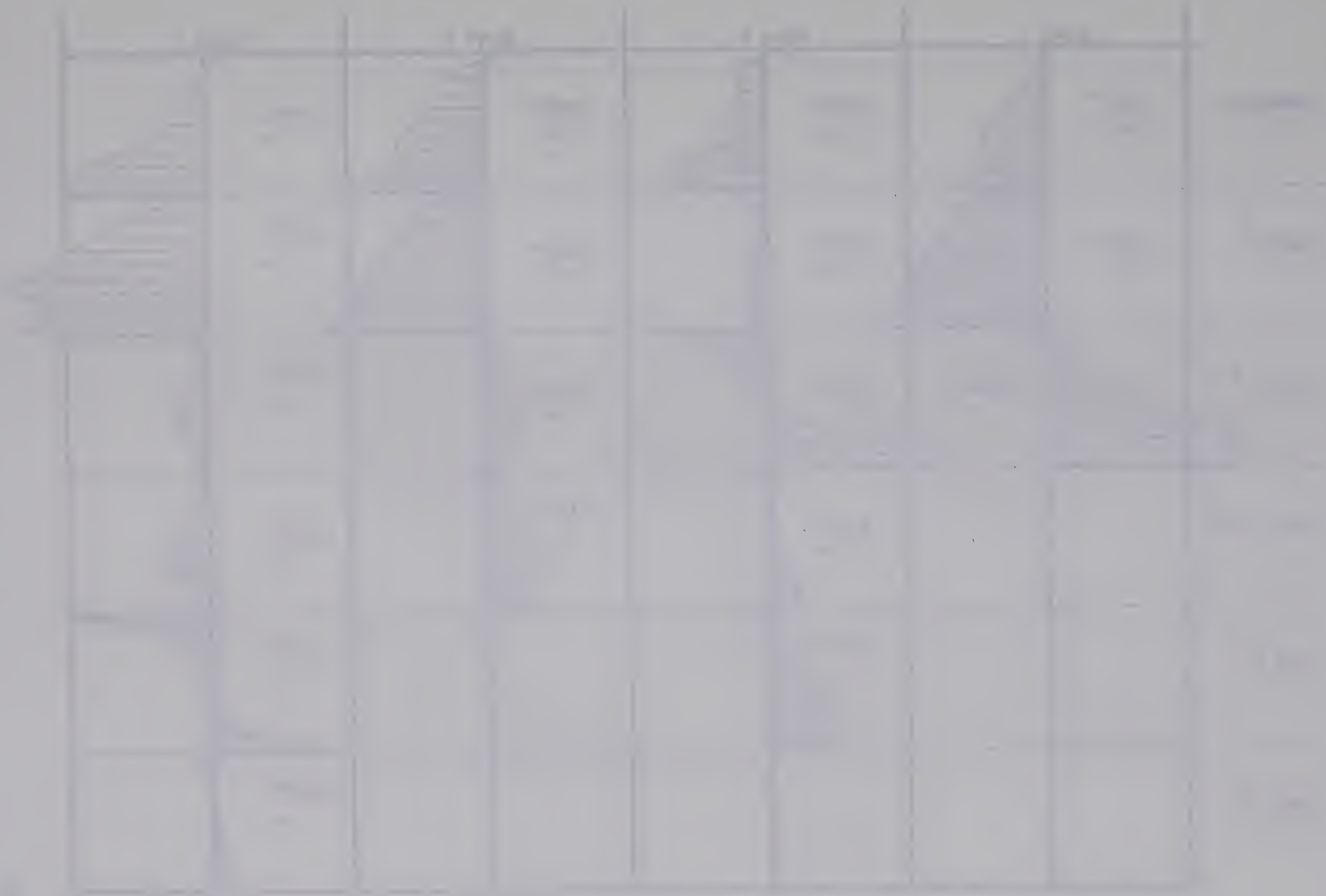


FIGURE 4.2(c) STRAIN DISTRIBUTION AT ℄ FOR BEAMS OF LOAD GROUPS 3 & 4



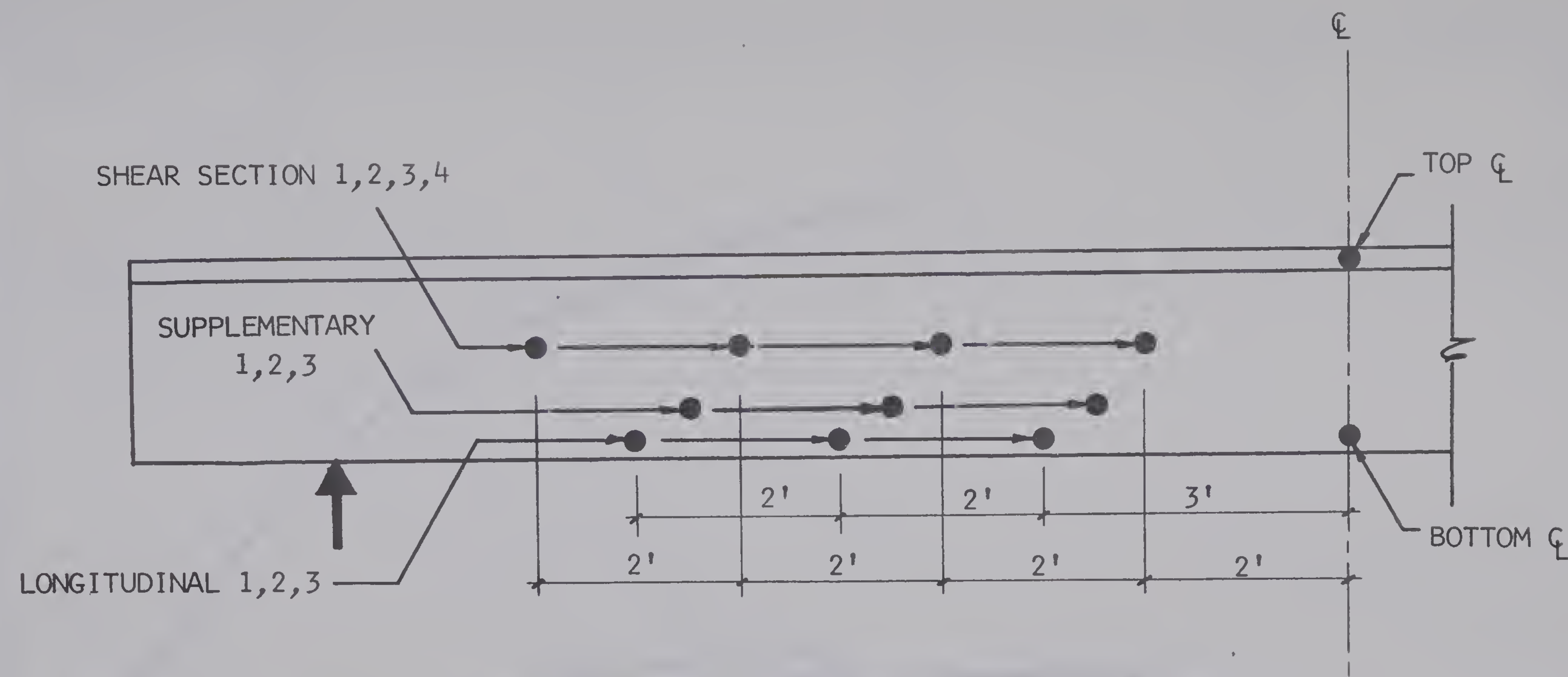


FIGURE 4.3 GENERAL STRAIN GAGE LOCATIONS

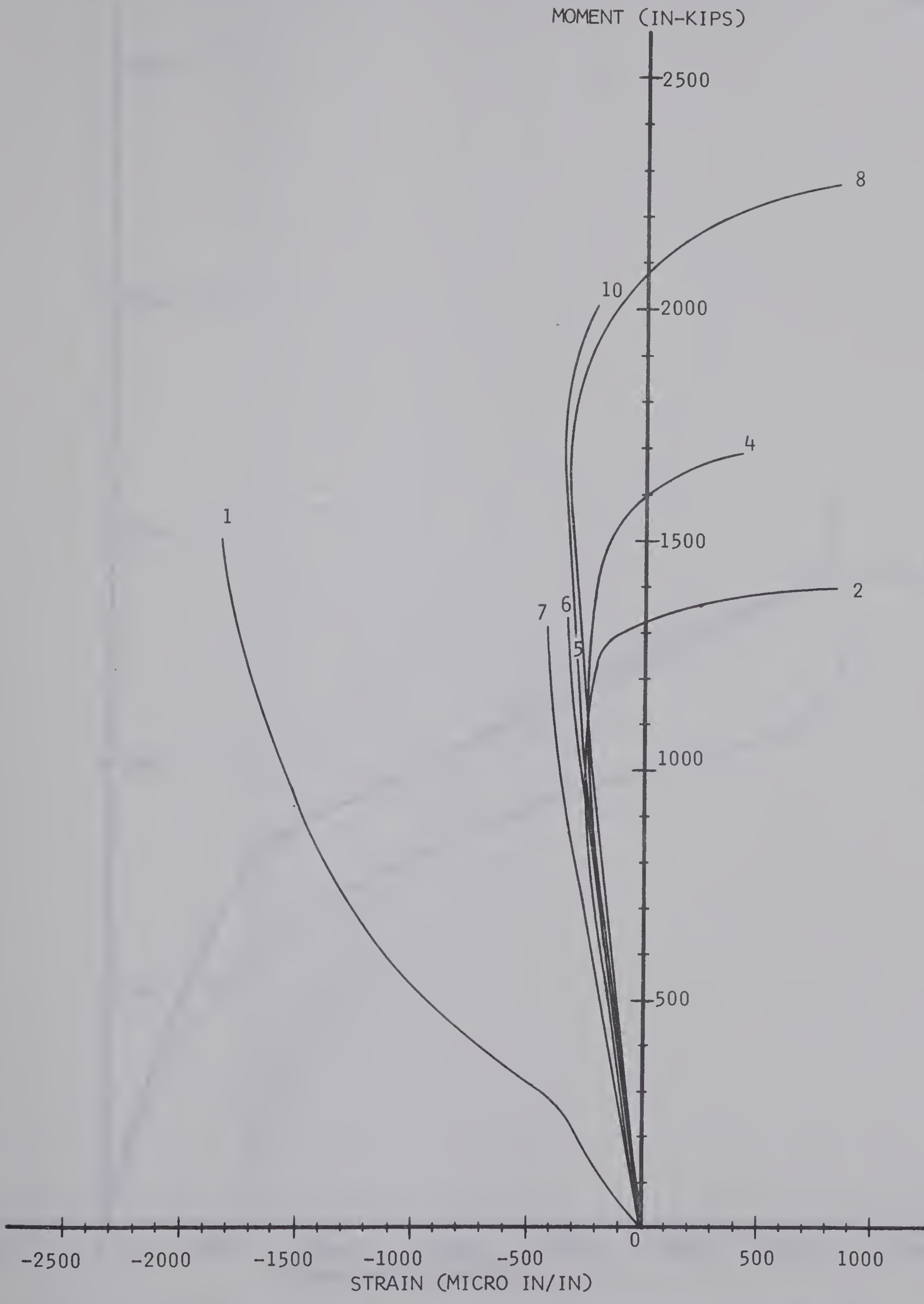


FIGURE 4.4(a) MOMENT-STRAIN RELATIONSHIP AT TOP ℄

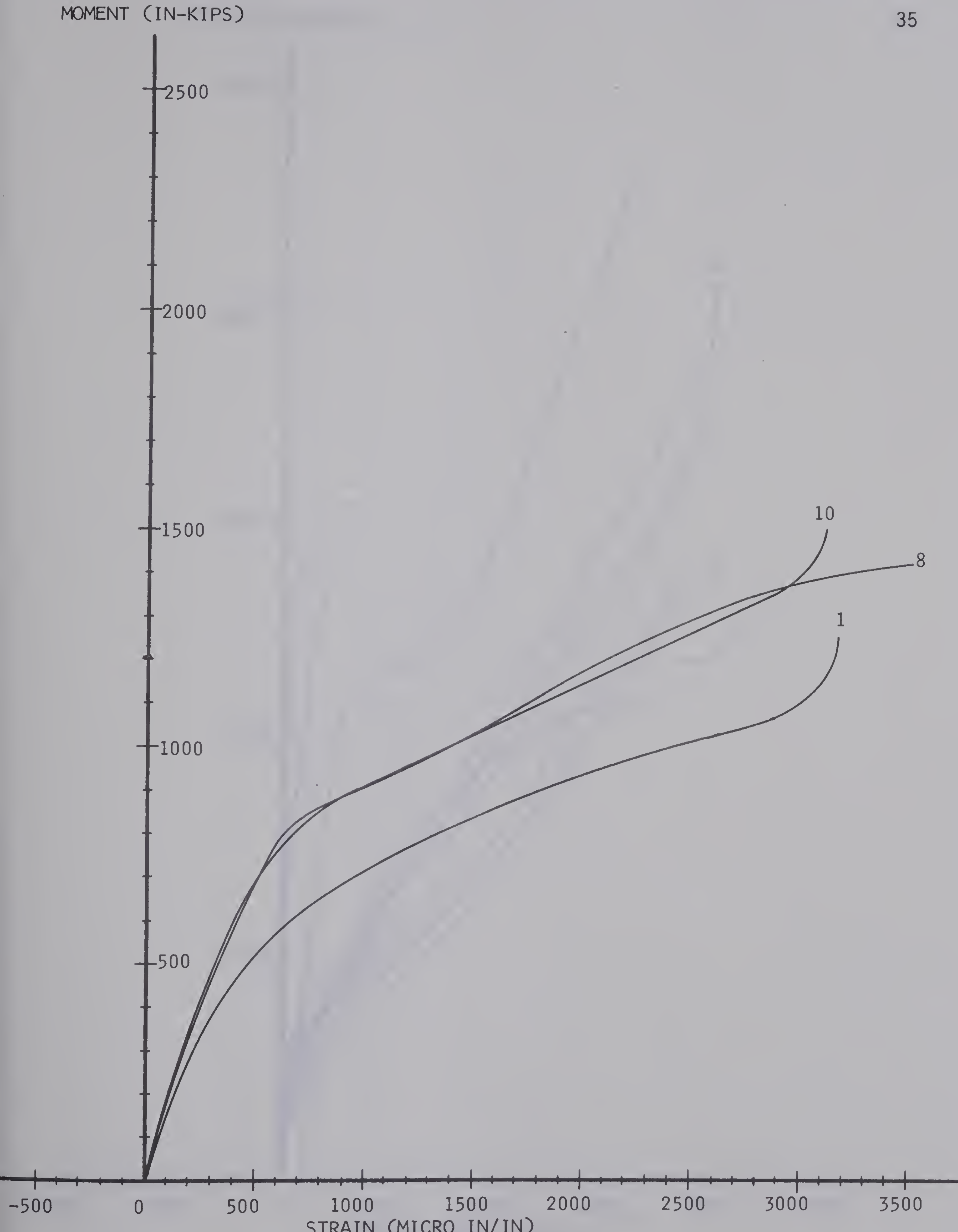


FIGURE 4.4(b) MOMENT-STRAIN RELATIONSHIP AT BOTTOM ℄

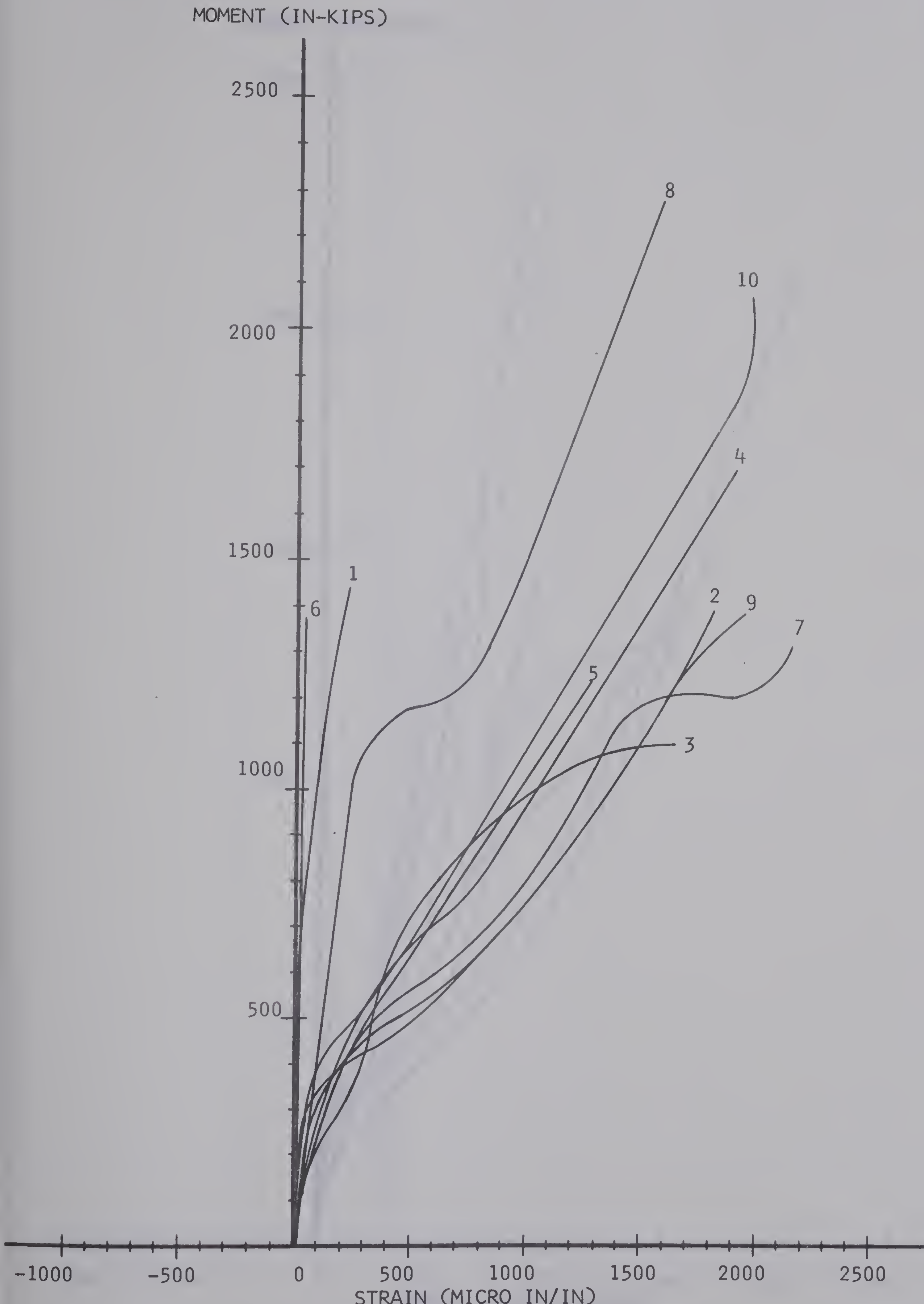


FIGURE 4.4(c) MOMENT-STRAIN RELATIONSHIP AT SHEAR SECTION 1

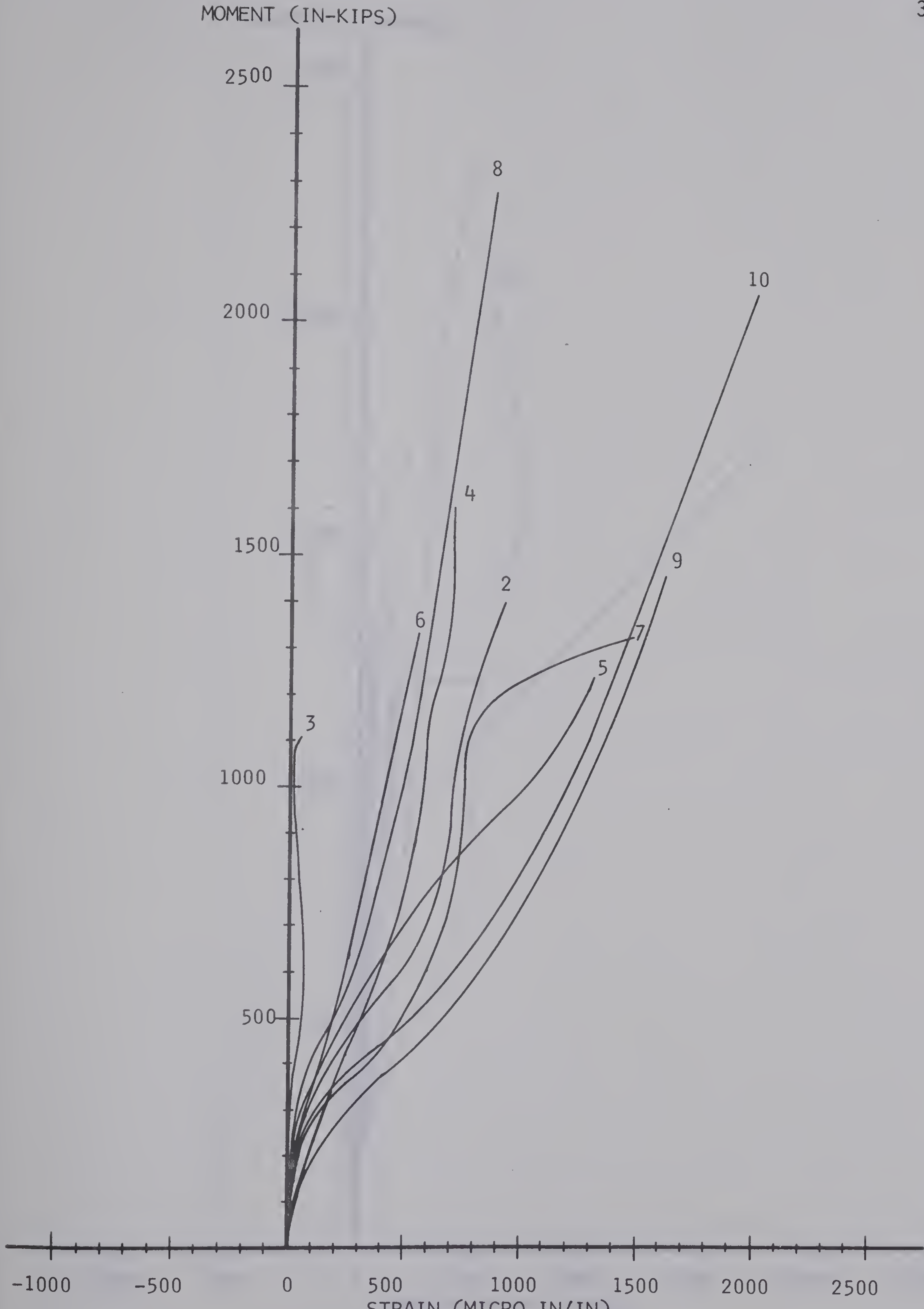


FIGURE 4.4(d) MOMENT-STRAIN RELATIONSHIP AT SHEAR SECTION 2

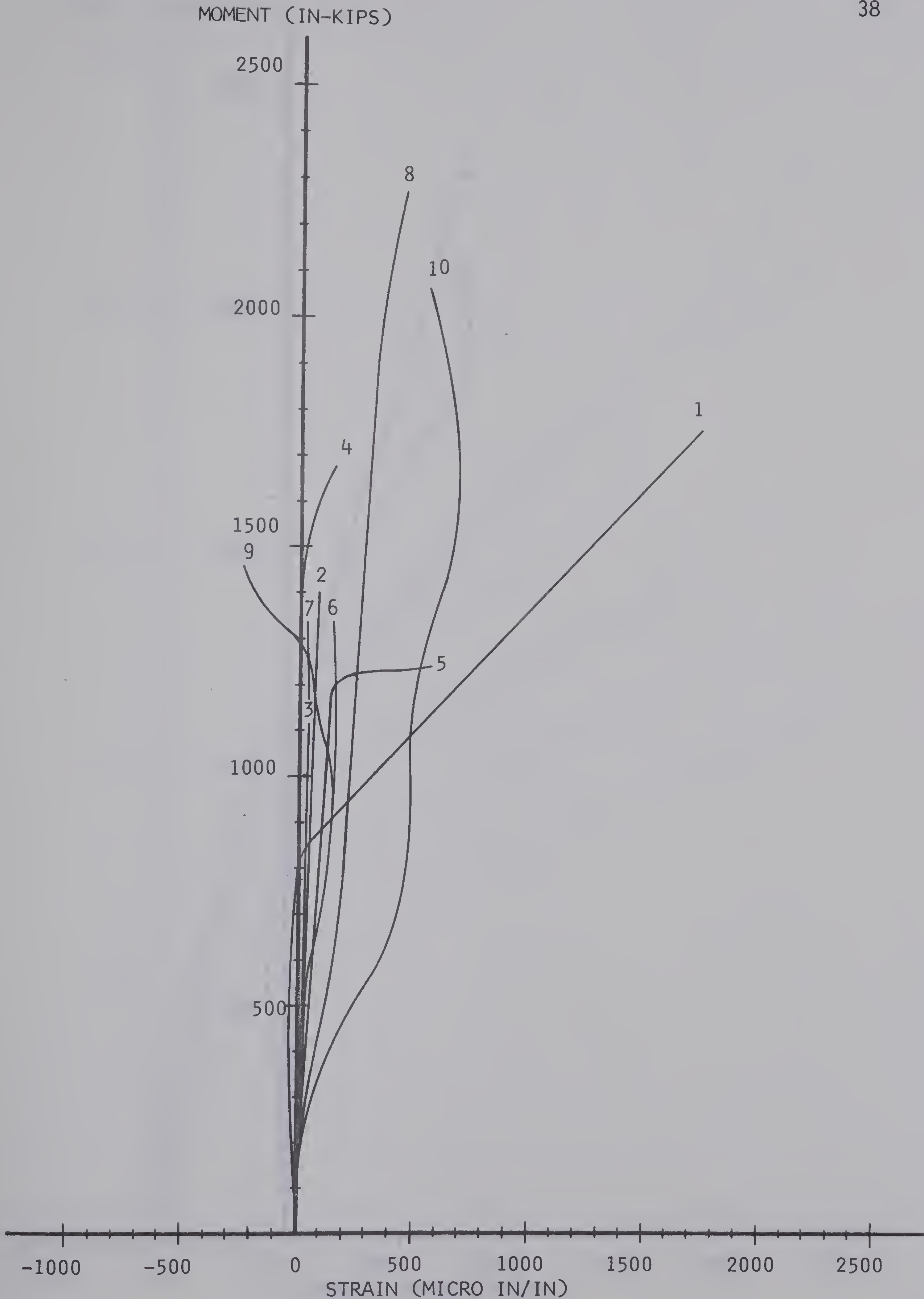


FIGURE 4.4(e) MOMENT-STRAIN RELATIONSHIP AT SHEAR SECTION 3

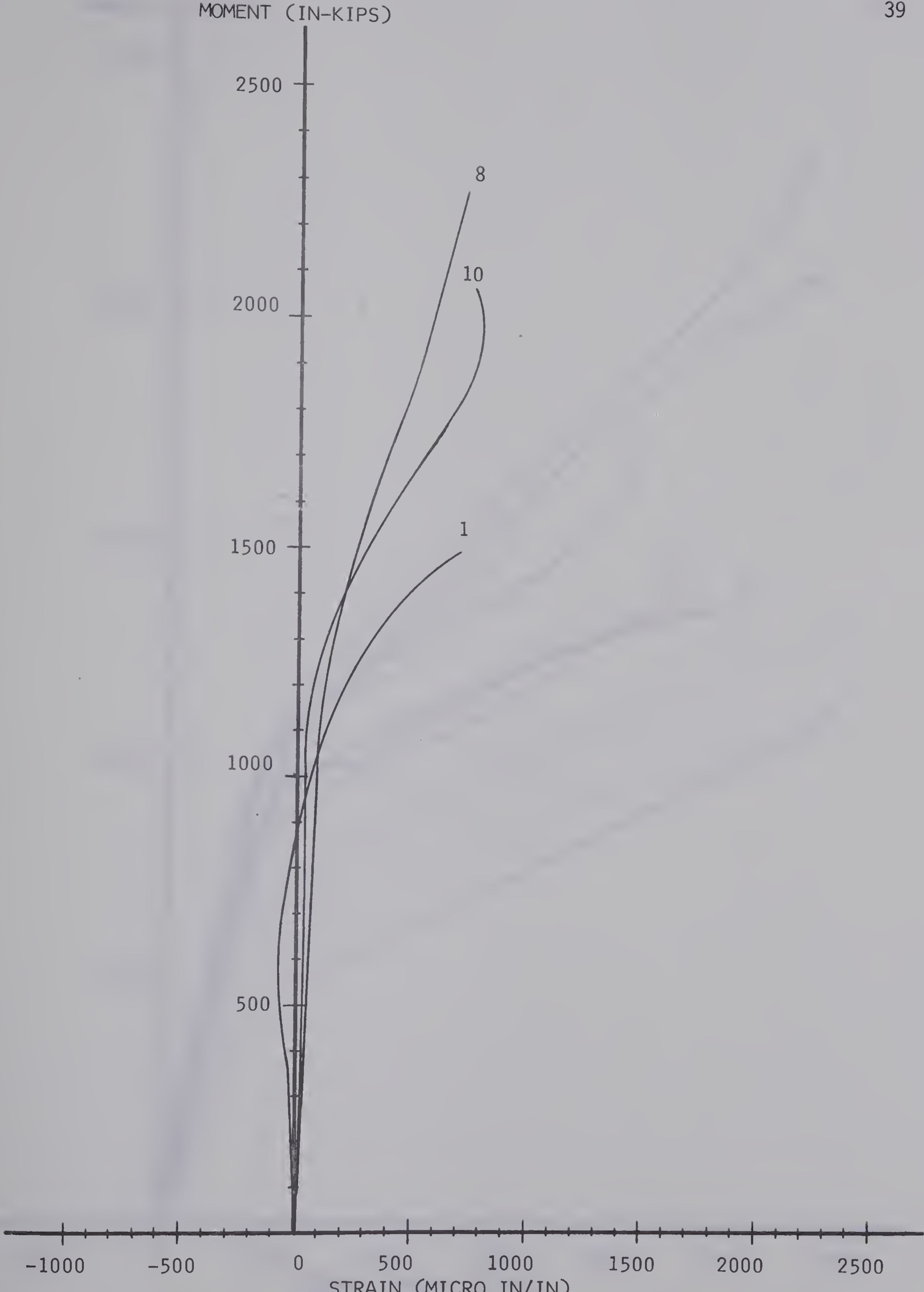


FIGURE 4.4(f) MOMENT-STRAIN RELATIONSHIP AT SHEAR SECTION 4

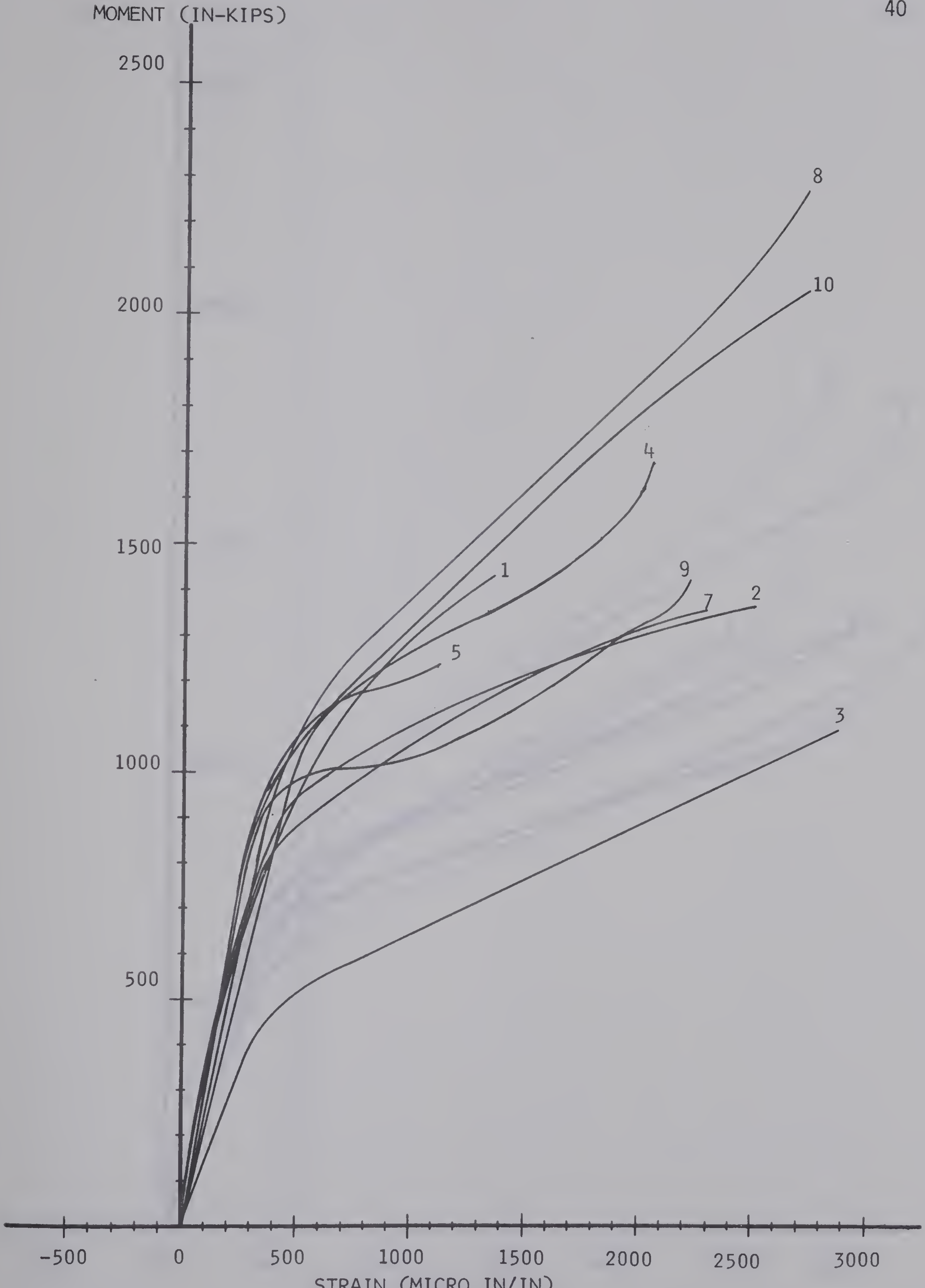


FIGURE 4.4(g) MOMENT-STRAIN RELATIONSHIP AT LONGITUDINAL 1

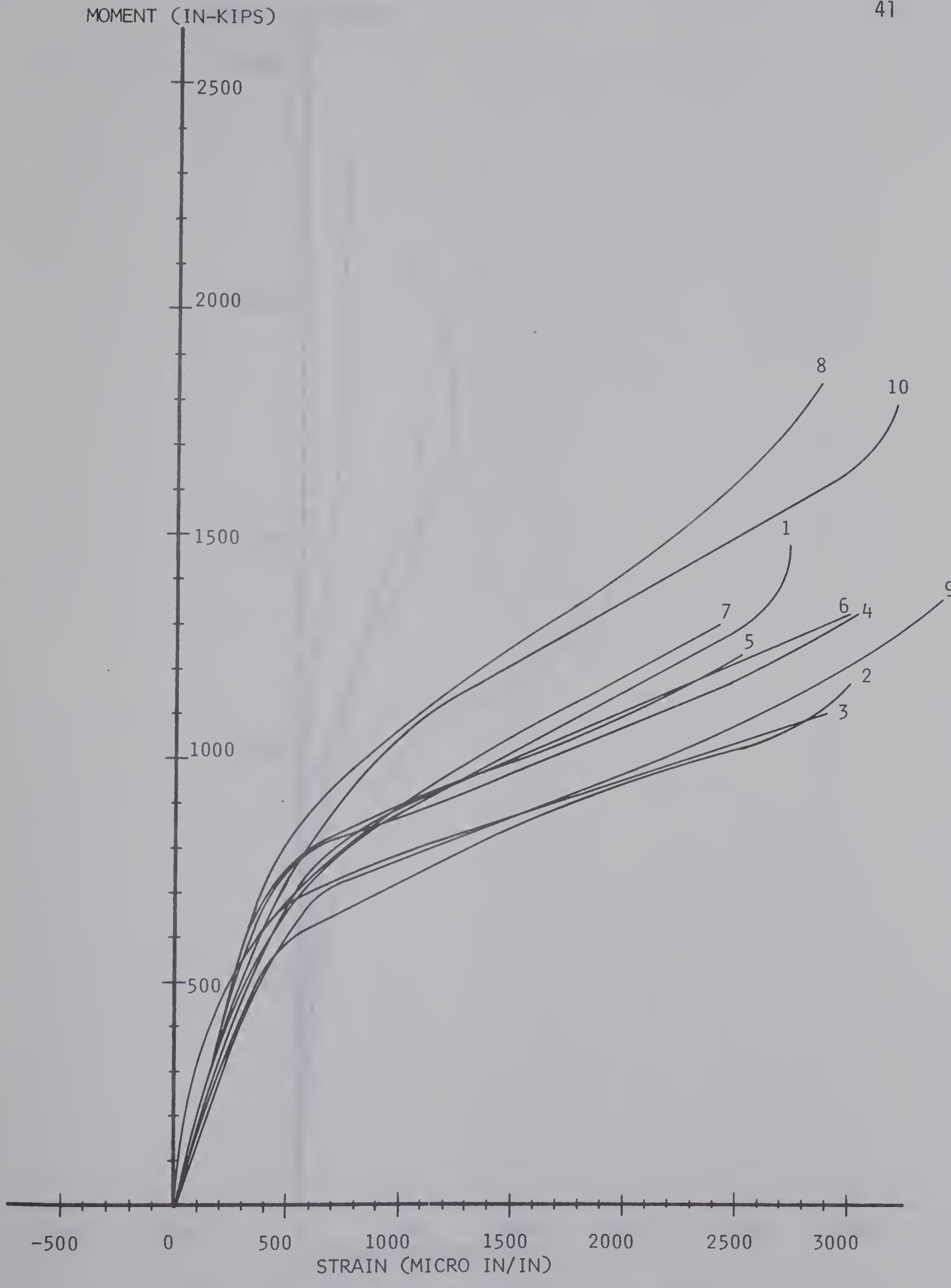


FIGURE 4.4(h) MOMENT-STRAIN RELATIONSHIP AT LONGITUDINAL 2

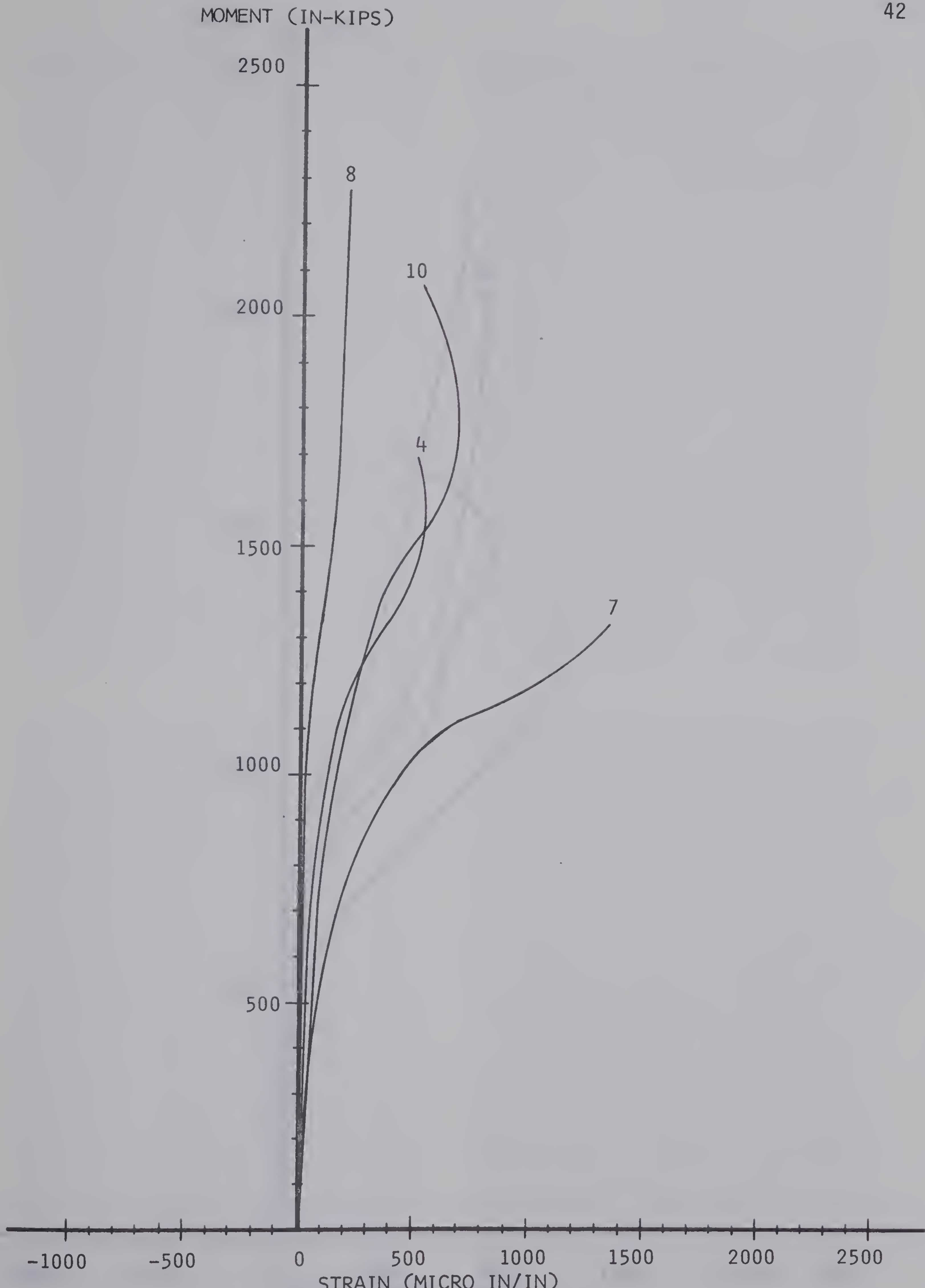


FIGURE 4.4(i) MOMENT-STRAIN RELATIONSHIP AT SUPPLEMENTARY 1

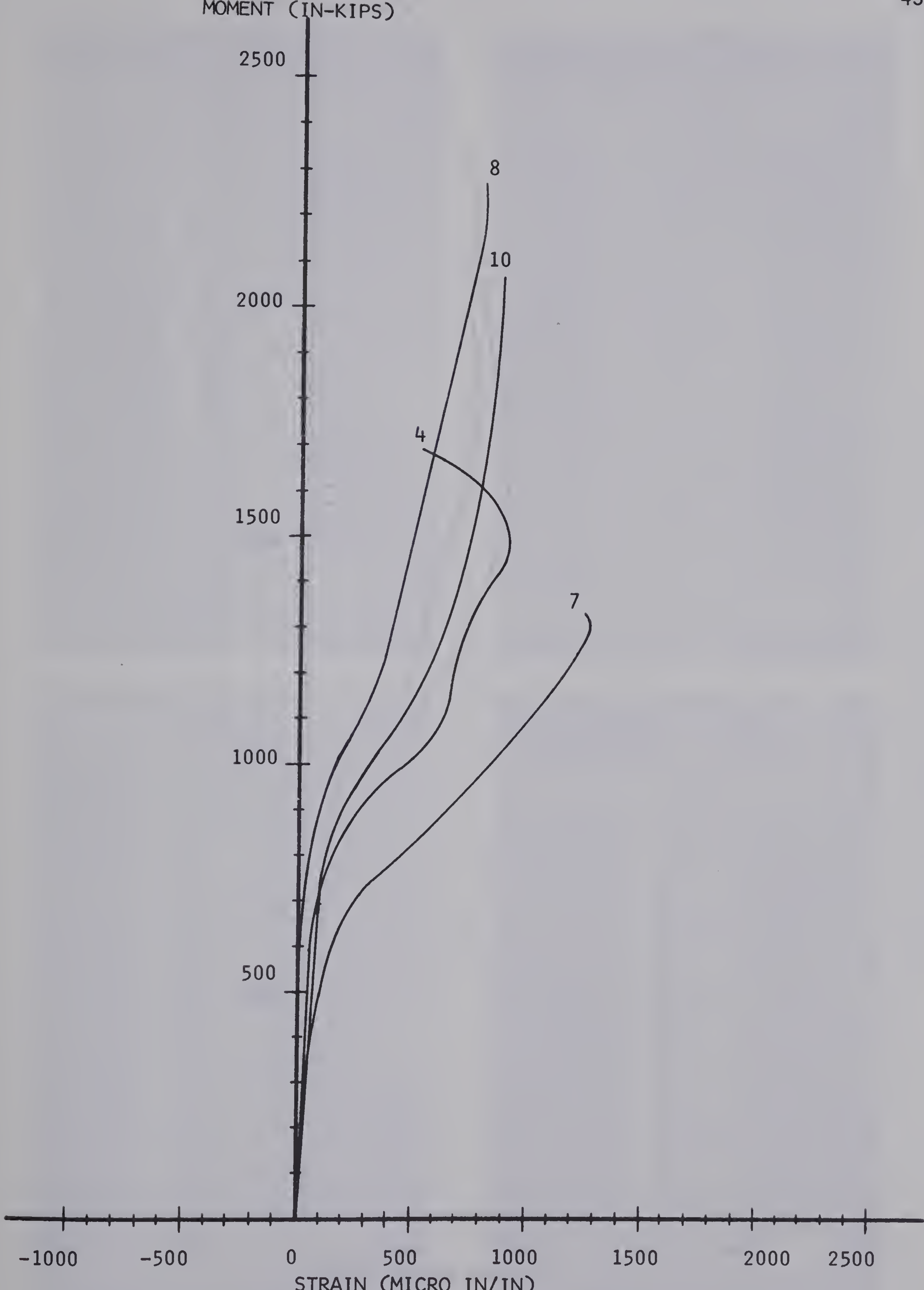


FIGURE 4.4(j) MOMENT-STRAIN RELATIONSHIP AT SUPPLEMENTARY 2

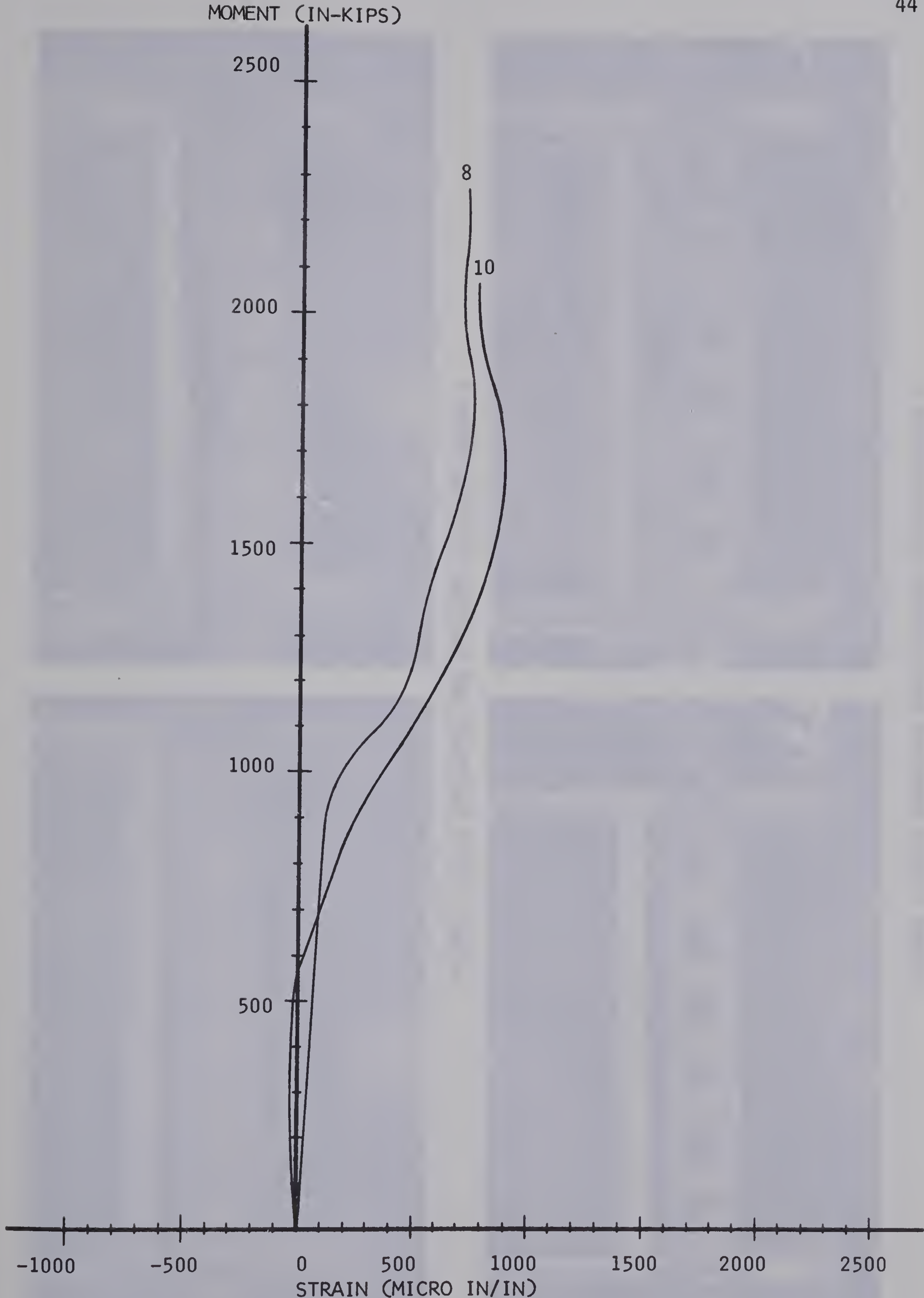
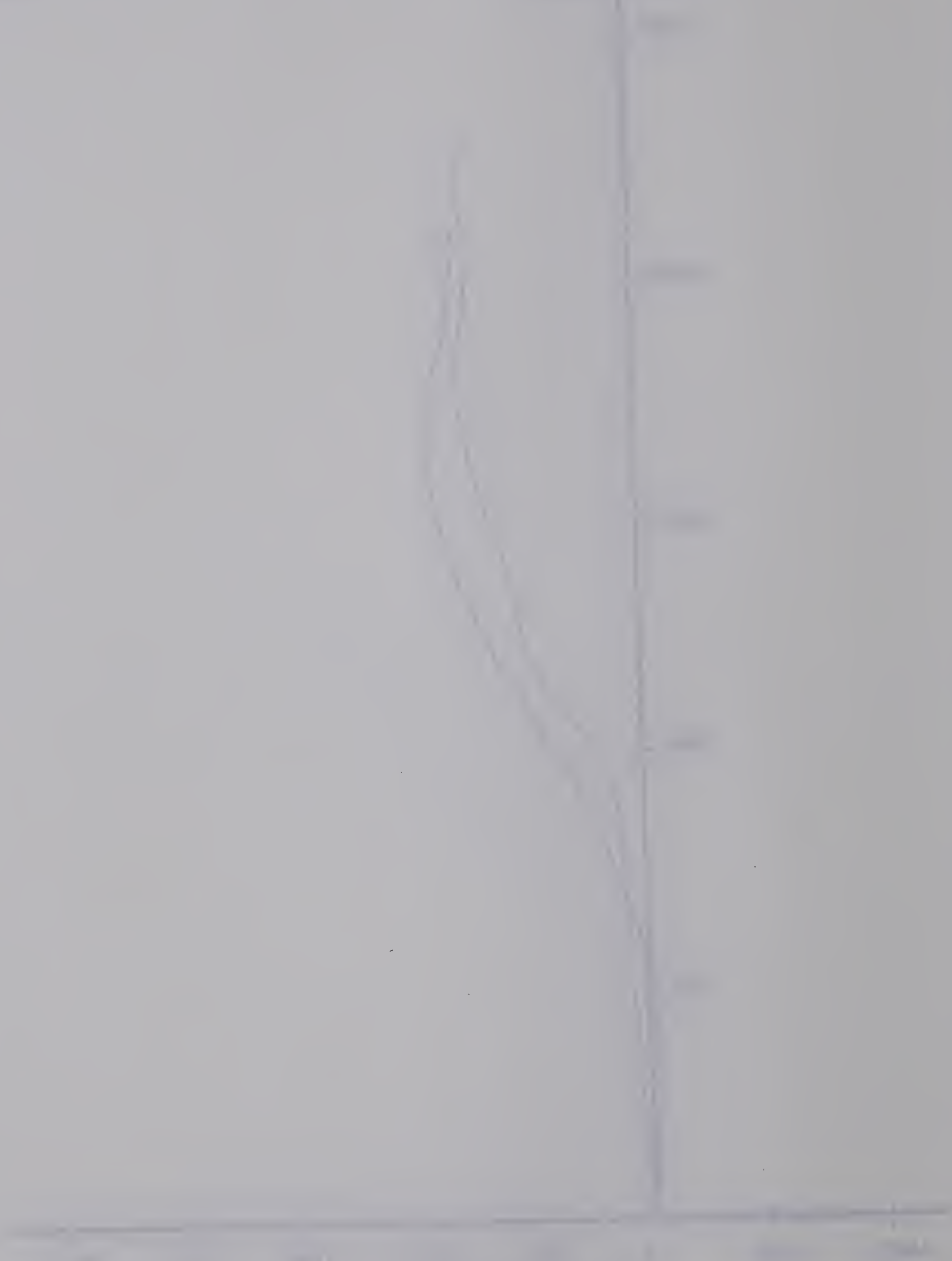


FIGURE 4.4(k) MOMENT-STRAIN RELATIONSHIP AT SUPPLEMENTARY 3



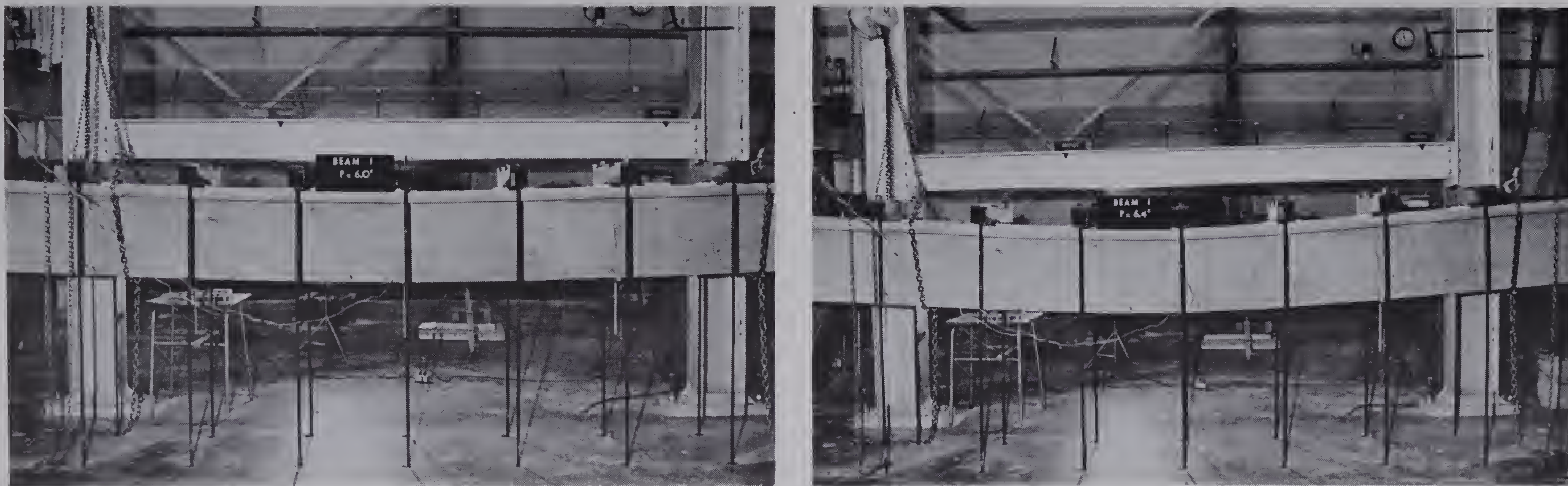


FIGURE 4.5(a) CRACKING AND FAILURE PATTERNS,BEAM 1

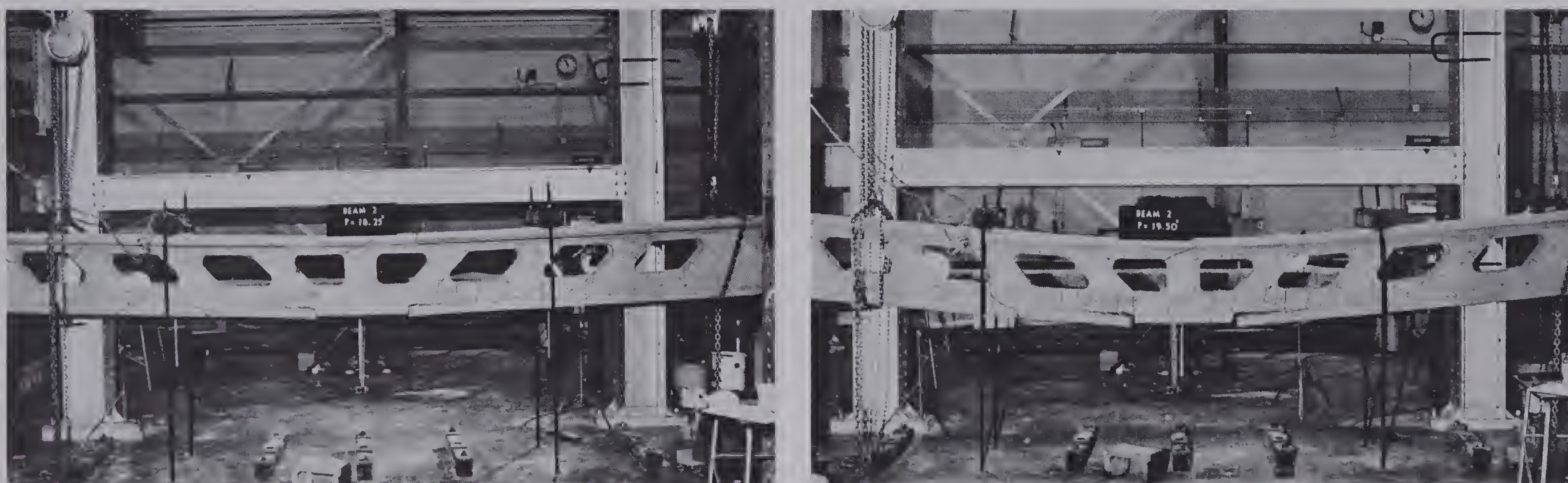


FIGURE 4.5(b) CRACKING AND FAILURE PATTERNS,BEAM 2

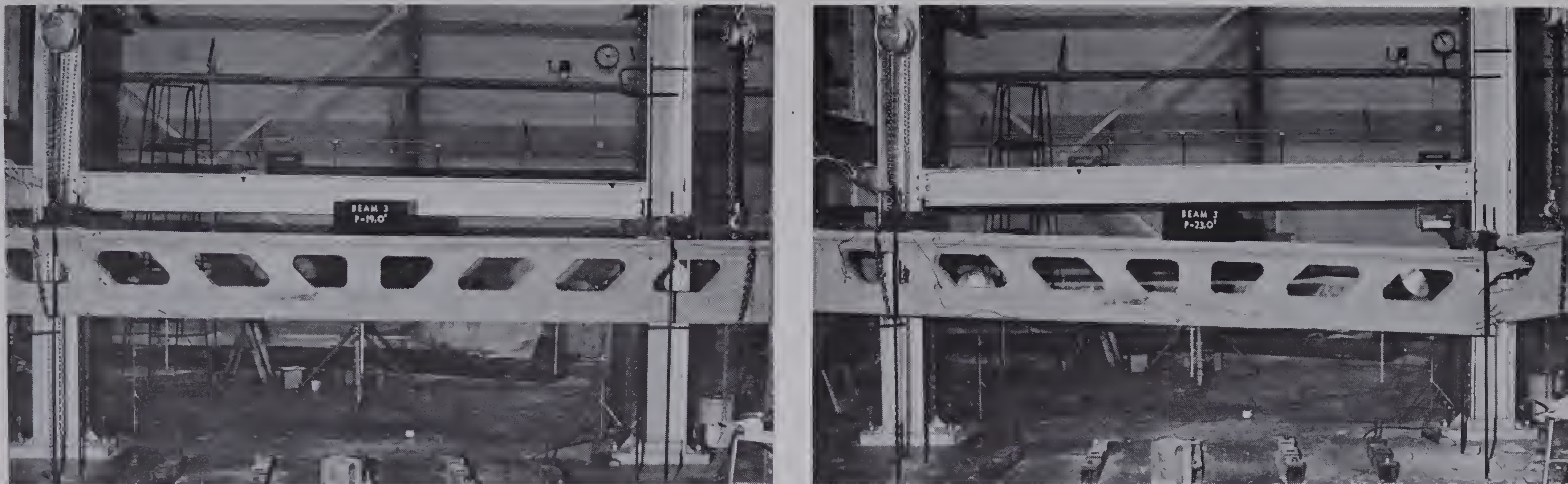


FIGURE 4.5(c) CRACKING AND FAILURE PATTERNS,BEAM 3

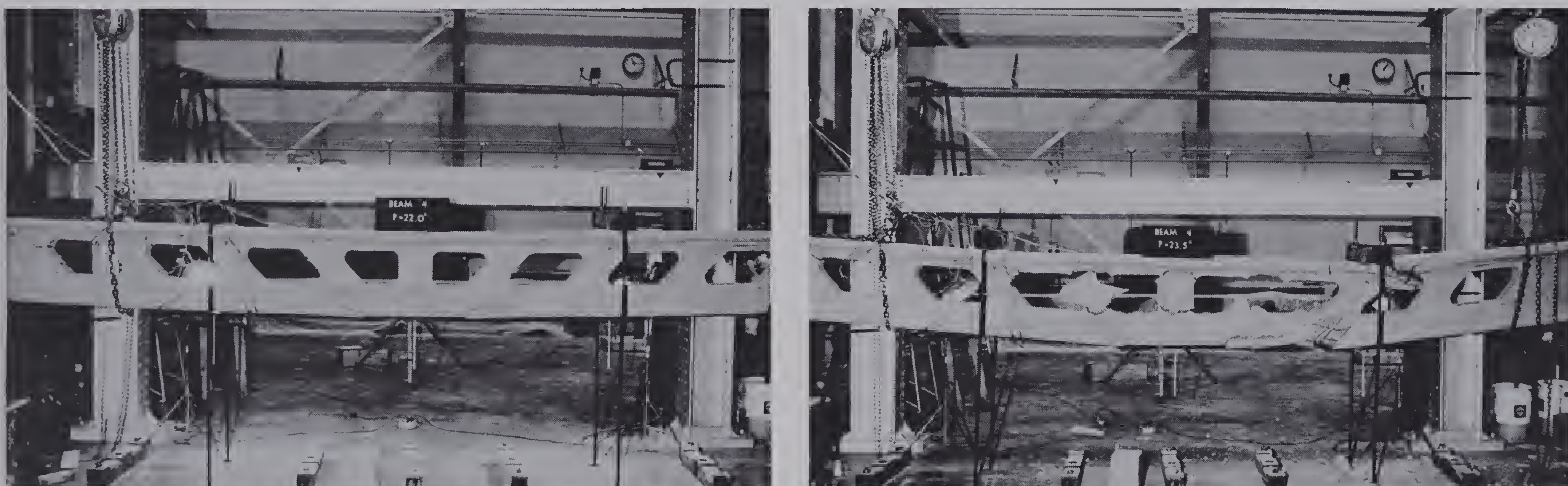


FIGURE 4.5(d) CRACKING AND FAILURE PATTERNS,BEAM 4

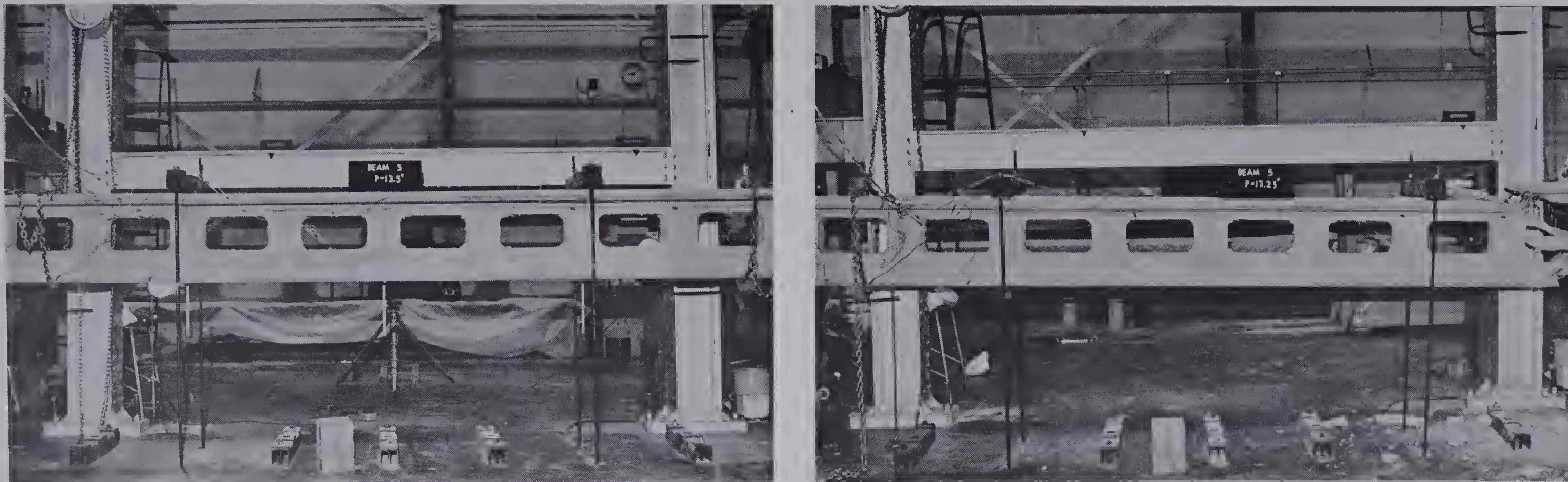


FIGURE 4.5(e) CRACKING AND FAILURE PATTERNS,BEAM 5

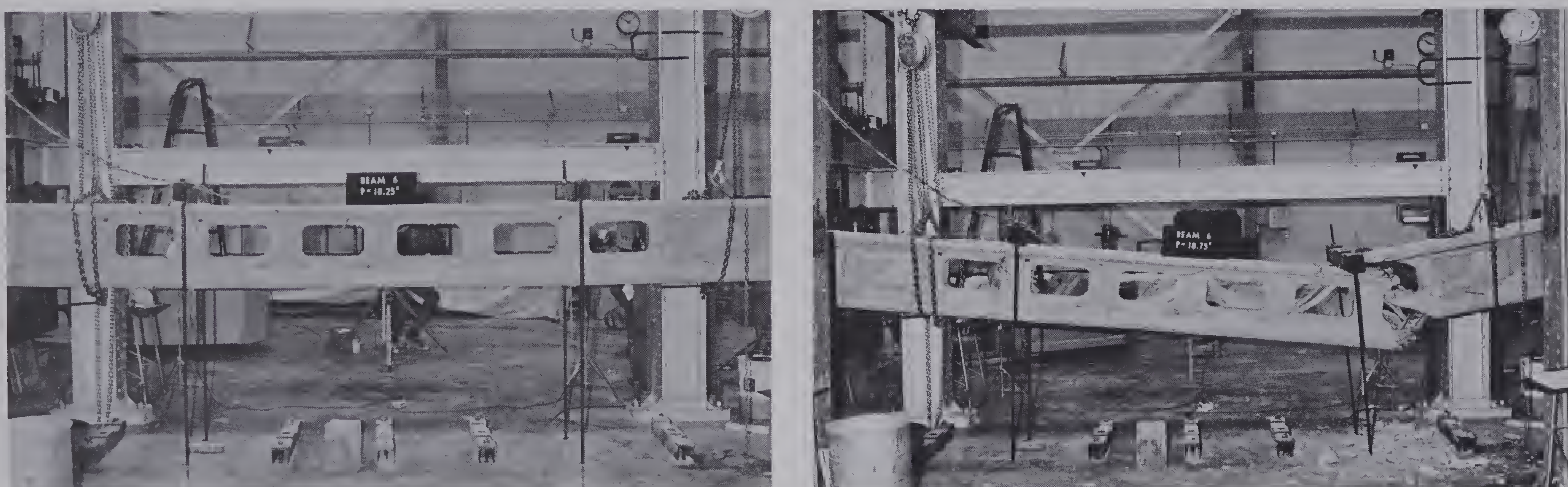


FIGURE 4.5(f) CRACKING AND FAILURE PATTERNS,BEAM 6

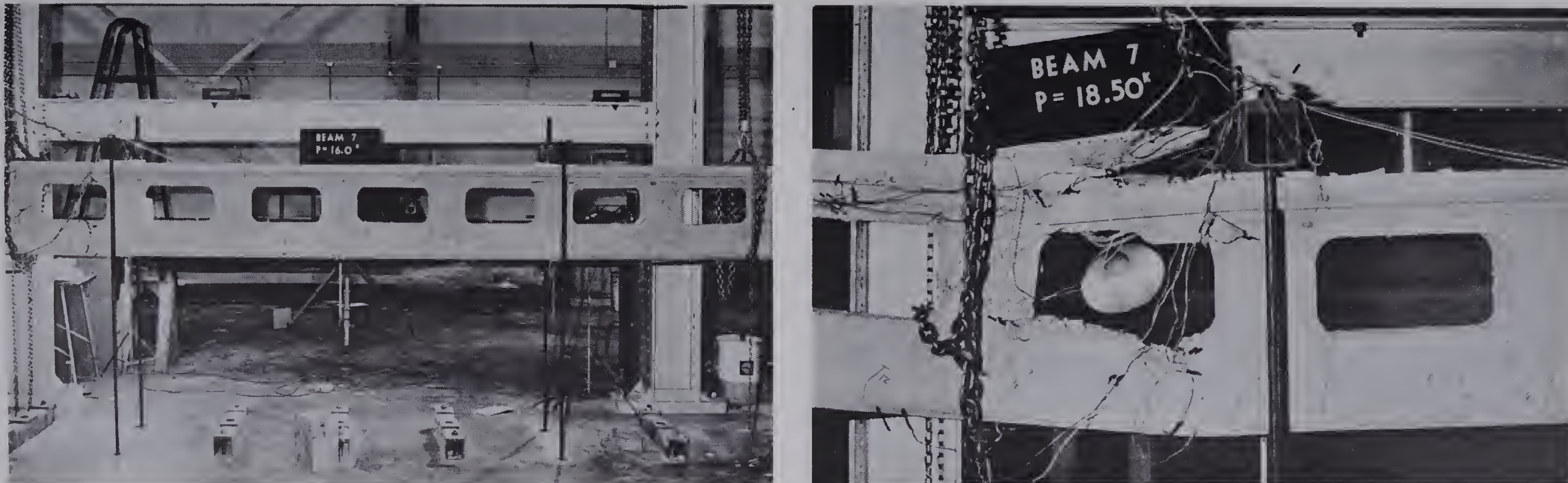


FIGURE 4.5(g) CRACKING AND FAILURE PATTERNS, BEAM 7

FIGURE 4.5(h) CRACKING AND FAILURE PATTERNS, BEAM 8

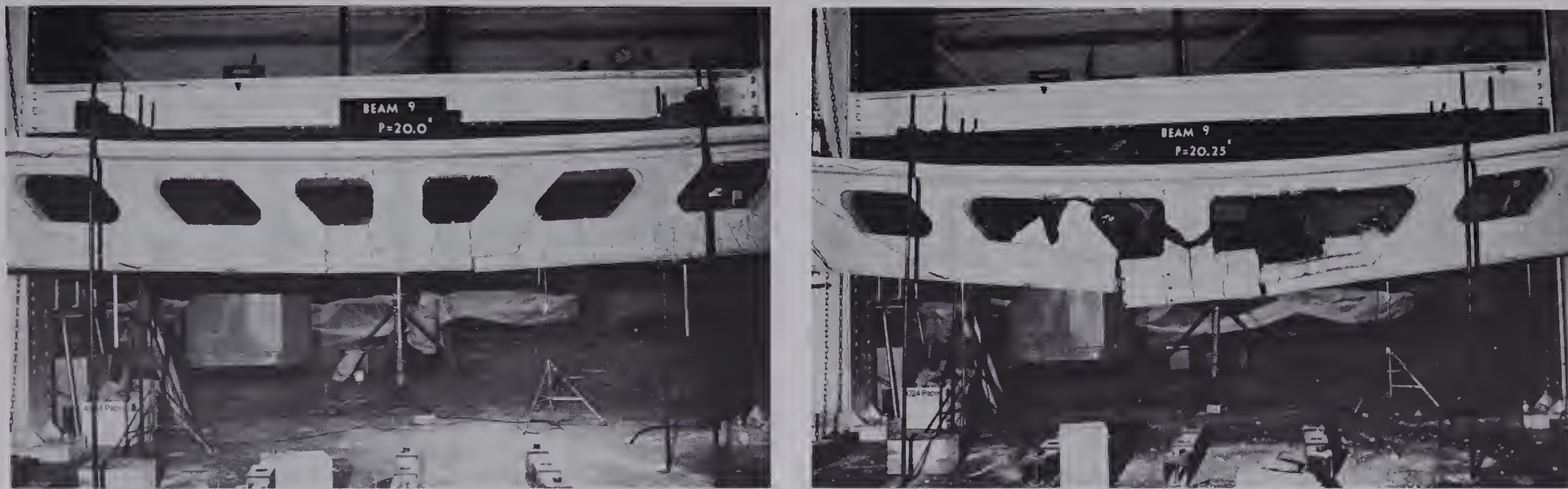


FIGURE 4.5(i) CRACKING AND FAILURE PATTERNS,BEAM 9

FIGURE 4.5(j) CRACKING AND FAILURE PATTERNS,BEAM 10

CHAPTER V

DISCUSSION

In this research program, ten beams were tested, nine of which contained large web openings and the other was used as a control beam. The parameters that were varied were: the shape of the web openings, the type of loading, the amount of prestressing force and the amount of shear reinforcement used. This chapter presents a discussion of the parameters, the behavior of the beams under load and the test results obtained. The type of loading used to test each beam was used as a means for grouping the beams into common groups. In this way, differences and similarities between members in each group could be compared as well as being able to compare the differences and similarities between different groups.

5.1 Control Beam

Beam 1 was fabricated for the purposes of comparison and contained no openings. It had 4 - 3/8 inch prestressing strands and its ultimate design capacity according to the ACI Code[1] was 1140 inch-k using fsu = 243.75 ksi, and 1295 inch-k using fsu = 275 ksi. The theoretical ultimate loads corresponding to these moments were 4.13 kips and 4.7 kips. The actual ultimate moment was 1766.4 inch-k with an ultimate load of 6.4 kips, which makes the ACI Code values seem quite conservative compared to the actual values. The first cracks appeared at a load of 2.4 kips per jack. At the ultimate load, all four prestressing strands broke. This beam was designed as an under-reinforced member

to fail as it did in flexure and not in shear. Design calculations are presented in Appendix C.

Beam 1 was designed and tested using a seven point loading. From its behavior during loading and up to failure, it can be said that it behaved as a typical under-reinforced prestressed tee beam. The cracking pattern can be seen from Figure 4.5(a). Cracking started mainly in the central portion of the beam and extended toward the end regions toward the latter stages of loading. At the ultimate load some of these cracks had reached the flange as is shown in Figure 4.5(a). However, none of the cracks opened up very wide, as two bars of #3 longitudinal reinforcement were placed all along the beam just below the four prestressing strands.

Shear reinforcement for this beam consisted of inclined stirrups spaced at 15 inches, all along the supported span. From the shear design calculations, inclined stirrups were required at a very large spacing (see Appendix C). A minimum spacing of 0.75 x depth is required for vertical stirrups in the ACI Code[1]. This minimum value is 15 inches, and was also used in this beam as a minimum requirement for inclined stirrups. Some cracks opened up along the length of these stirrups toward the final loading stages (see Figure 4.5(a)).

From the strain distribution measurements at the centerline, Figure 4.2(a), it was noted that the neutral axis was in the lower part of the flange at the failure load. From the moment strain relationship at the top centerline, Figure 4.4(a), it can be seen that the gage in beam 1 at this location was in compression throughout the test, and therefore always above the neutral axis.

Failure of this beam ultimately was caused by the visible fracture of all four prestressing strands. The strands broke at the longitudinal beam centerline. The total deflection at the centerline just before failure was 6.1 inches.

5.2 Discussion of Beam Parameters

The most important parameter in this investigation was the shape of the web openings. This also meant using shear reinforcing stirrups at different angles. From previous investigations, on types of shear reinforcing for beams, inclined shear stirrups have proven to be more effective in resisting shear and diagonal stresses due to applied loads. Parallelogram shaped openings, compared to rectangular openings, not only change the stress concentrations to the beam under load, but also require the use of inclined stirrups. However, in changing from rectangular openings to parallelogram shaped openings, the total area of openings was reduced by 11.8%, that is, from 996 in^2 to 878 in^2 for eight openings. This is a result of the shape of the openings adjacent to the centerline and the effect of the fillets in the corners of the openings.

The type of loading was the second most important variable. A seven point loading was used for Beams 1, 8 and 10. Two point loading was used for the remaining beams. Beam 3 had two point loads at 12 feet centers and the remaining 6 beams had two point loads at 8 feet centers. Varying the type of loading meant varying the shear and bending stresses along the supported span of the beam. For this

reason the design for shear was based on the type of loading to be carried during the actual test. This is shown in Figure 3.4 and also in Appendix C.

The remaining variables consisted of: the number of prestressing strands varied from 4 strands to 5 strands to increase the flexural strength of the beams; the spacing of shear stirrups, along with the number of stirrups per post; and finally the supplementary shear reinforcing in the lower web. This supplementary shear reinforcing in the lower web consisted of simple U stirrups placed under the web openings and inclined at 45° to the horizontal, as shown in Appendix B, Figures B.4.1, B.7.1, B.8.1 and B.10.1.

An increase in the number of strands from 4 strands to 5 strands meant an increase in the flexural strength of the beam. This in turn meant, that to achieve the ultimate flexural capacity of the beam, the beam had to resist higher shear stresses and therefore extra provisions in the form of shear reinforcing, had to be provided. The weakest part of the beams with openings, appeared to be the flange of the beam above the holes, in the high shear region. In all cases where a shear failure occurred, it occurred at this location. However, due to the small thickness of the flange, and the limited working space within the forms in this area, extra shear reinforcing could not be provided.

Varying the spacing of the shear stirrups and increasing the number of stirrups per post in every case, added some strength and stiffness to the beam, however, failure never occurred through the posts or between the last outside hole and the support, but it always occurred

in the case of a shear failure, through a hole section. In the beams where supplementary shear reinforcing in the lower web was provided, this added strength to the beam and contributed to a more ductile type of failure, for those beams that failed in shear.

As previously stated, the beams were arranged into groups according to the type of loading used during the test. The beams of group 1, Beams 1, 8 and 10, all were designed for, and tested under, seven point loading. Beam 1 had 4 strands and no openings while Beams 8 and 10 had 5 strands and parallelogram shaped openings. Beam 10 was the same as Beam 8, except for the stirrup spacing, which was increased, and the number of stirrups per post was reduced from four to two. The failure load for Beam 8 was predicted from the observed failure load of Beam 1, by proportion, using the ACI Code[1] theoretical ultimate loads for the beams with 4 strands and that with 5 strands respectively. This computation yields: $6.4 \times 5.17/4.13 = 8.0$ kips.

The actual ultimate load of Beam 8 was 8.25 kips and that for Beam 10, which differed from Beam 8 only in shear reinforcing, was 7.5 kips.

Load group 2, consisted of Beams 5, 6 and 7. These three had rectangular openings and were prestressed with 5 strands. Beam 5 had less shear reinforcing than Beams 6 and 7. Beam 7, in addition, had some supplementary shear reinforcing in the lower web. After Beam 5 had been tested and a shear failure occurred through the outside hole section in the shear span of the beam (Figure 4.5(e)), it was decided that the outside holes in Beam 6 would be filled with concrete so as to change the behavior of the beam, and shift the failure to another

location (see Figure 4.5(f)). This gave a total hole area of 747 in^2 for 6 rectangular openings, compared to 996 in^2 for 8 rectangular openings. Beam 7 failed in shear in almost the same manner as did Beams 5 and 6, however, due to the addition of supplementary shear reinforcing in the lower web, a more ductile type of shear failure occurred (see Figure 4.5(g)).

Load group 3 consisted of Beams 2, 4 and 9. This group all had two point loading, spaced at 8 feet centers and all had 8 parallelogram shaped openings. Beams 2 and 9 contained 4 strands, while Beam 4 contained 5 strands. Beams 2 and 9 were identically designed and tested, except that Beam 2 had less shear reinforcing than Beam 9. Beam 4 which contained 5 strands, had much more shear reinforcing than either of Beams 2 or 9, as shown in Figure 3.4. A flexural failure by rupturing of the strands occurred for Beams 2 and 9, however, for Beam 4 due to the higher flexural strength and therefore higher shear stresses approaching the flexural capacity of the beam, the beam failed in shear through the first hole to the right of the right hand load point. An explosive type of failure resulted (see Figure 4.5(d)).

Load group 4 consisted of Beam 3. This beam was alone in its group because it was tested under severe shear conditions, that is, two point loading was used spaced at 12 feet centers. Failure occurred through the outside hole on the right hand side next to the load point, as shown in Figure 4.5(c).

5.3 Load Group 1

Beams 1, 8 and 10 comprising this group were tested under seven point loading and all failed in the flexural mode. In each case the strands fractured, resulting in an abrupt drop in the load carrying capacity of the beam. Beam 1 was the control beam and had no openings while Beams 8 and 10 had parallelogram shaped openings.

These three beams failed in a ductile manner, typical of under-reinforced prestressed concrete tee beams. In Beams 8 and 10, cracking was extensive in the lower web throughout the loading region. Ultimate rupture of the strands in both cases, occurred just to the left of the centerline of the beam. In Beams 1, 8 and 10, all of the strands (4, 5 and 5 respectively) broke at the ultimate load.

Beam 10 is identical with Beam 8 except for the stirrup spacing and the number of stirrups per post. Beam 8 had four stirrups per post with a 5 inch spacing in the solid shear span, compared with Beam 10, which had a 12 inch spacing in the solid shear span, and two stirrups per post. Beam 10 was sufficiently reinforced for shear stresses, to be able to reach its ultimate flexural strength under seven point loading, however, as already mentioned, its ultimate load was less than that of Beam 8 by 0.75 kips. The difference in these ultimate loads may probably be attributed to the fact that the prestressing strands for these two beams came from different rolls.

Beam 4 in load group 3 is similar to Beam 8 of this load group, except that Beam 4 was designed for two point loading spaced at 8 feet centers. Beam 4 failed in shear or combined shear and bending, due to

the higher shear stresses existing between the load points and the support.

This load group displayed the effectiveness of inclined shear stirrups. Beams 8 and 10 had no severe cracking in the posts at the ultimate load. These beams acted like a homogeneous mass, quite similar to Beam 1. The ultimate flexural capacity of Beams 8 and 10 was about as high as would be expected from a similar beam without web openings.

5.4 Load Group 2

Beams 5, 6 and 7 of this load group containing rectangular openings, were designed as a direct continuation of Sauve's[7] work using rectangular openings. These beams contained 5 prestressing strands, compared to Sauve's which all contained 4 strands. Beam 5 was identical with Sauve's Beam 5, except for the amount of prestressing strands used. A shear failure was anticipated here, through the outside hole and this is what occurred. This type of shear failure is rather a combined shear and bending type of failure. As seen in Figure 4.5(e), a type of mechanism forms and a shear as well as a longitudinal shift occurs. This shear failure was typical of all of the shear failures which occurred in this series, as well as some of those which occurred in Sauve's tests. In Beam 5, there was no lower web reinforcing, and thus, a lower load resulted in failure for this beam. With no lower web reinforcing the failure was more explosive and also more complete, that is, the load carrying capacity of the

beam was completely lost at failure.

Beam 6, which had more stirrups per post and a closer stirrup spacing than Beam 5, also as previously mentioned, had its two end holes filled with concrete to shift the failure over to the hole section next to the load point (see Figure 4.5(f)). The failure occurred as anticipated, and was very similar to that of Beam 5. The cracking patterns for Beams 5 and 6 were also similar. Beam 6 had a higher ultimate load (18.75 kips) than Beam 5 (17.25 kips), because Beam 6 had a smaller hole area. Beam 6 had a hole area of 747 in^2, compared to Beam 5 with a hole area of 996 in^2.

Beam 7 had the same stirrup spacing and number of stirrups per post as Beam 6, however, Beam 7 also had lower web reinforcing in the shear span. This lower web reinforcing served to increase the ultimate load from that of Beam 5, and also to create a more ductile type of failure. This failure did not completely remove the load carrying capacity of the beam.

From this loading group, it can be seen, that lower web reinforcing definitely raises the ultimate load, as well as creates a more ductile type of shear failure. A close spacing of stirrups in the posts in the shear spans serves to stiffen the posts, but is not really necessary as failure occurs through the hole section. (The fracture of the post in Beam 7, shown in Figure 4.5(g), occurred after the shear failure in the flange and lower web.) Upper web and flange shear reinforcing, over the holes in the shear span, would strengthen these beams against such shear failures.

5.5 Load Group 3

Beams 2, 4 and 9 of this load group were all designed for and tested using a two point loading, spaced at 8 feet centers. All contained parallelogram shaped openings.

Beam 2 contained three stirrups per post and had an 8 inch spacing of stirrups, while Beam 9, had two stirrups per post with a 12 inch stirrup spacing. These two beams were exactly similar in other respects, and both contained four prestressing strands. Both of these beams failed by fracture of the 4 prestressing strands. Beam 2 had a more ductile type of failure, possibly due to the larger amount of shear reinforcing incorporated in it. In this beam, the strands ruptured just below the first hole on the left side of the centerline (see Figure 4.5(b)). Beam 9 on the other hand had a more explosive type of failure. The three posts in the pure moment span, were sheared off when the 4 prestressing strands broke, as can be seen in Figure 4.5(i). A slightly higher ultimate load was sustained by Beam 9 than Beam 2. This was not anticipated and is probably due to differences in material properties between the two beams. Figure 4.5(i) shows that the posts in the shear span of Beam 9, which contained inclined shear stirrups, were still intact after the beam had failed.

Beam 4 was similar to Beams 2 and 9, however, it contained 5 prestressing strands and it also contained more shear reinforcing than Beams 2 and 9. Beam 4 had a stirrup spacing of 5 inches and contained 4 stirrups per post. As previously stated, Beam 4 was similar to Beam 8, except that Beam 4 was designed for two point loading and Beam 8

for seven point loading.

Beam 4 failed in shear in an explosive manner, as shown in Figure 4.5(d), although it was anticipated that a flexural failure might occur. The three center posts in the pure moment span were sheared off at either end, when the energy from the failure was released. Due to the presence of lower web reinforcing, only the upper web and flange, above the opening to the right of the right load point, were sheared at failure. The lower web below the hole was still intact after failure as seen in Figure 4.5(d). This beam would probably have failed in flexure if it had been tested with a seven point loading, due to the less severe shear condition present in this type of loading. This beam was a much stronger beam than Beams 2 and 9. Its ultimate load was 23.5 kips, compared to that of Beam 2, with an ultimate load of 19.5 kips and that of Beam 9, with an ultimate load of 20.25 kips. The higher load at failure of Beam 4, explains the explosive behavior which occurred. This beam would probably have failed in flexure if shear reinforcing had been provided in the flange and upper web of its shear span. This shear failure again is a type of combined bending and shear failure, which was common in Beams 5, 6 and 7.

5.6 Load Group 4

This loading group consists simply of Beam 3. Beam 3 was the only beam of this series to be loaded with a two point loading, spaced at 12 feet centers. It failed in shear, and the failure was very similar to the failures of Beams 5, 6 and 7 with rectangular openings. Beam 3

contained only 4 strands; it had a stirrup spacing of 5 inches and 4 stirrups per post in the shear span. This beam was originally designed for a two point loading spaced at 8 feet centers, however, due to the previous test results, this loading plan was changed to two point loading spaced at 12 feet centers. The typical shear failure obtained, as seen in Figure 4.5(c), also was accompanied by an explosive type of energy release, which produced long, wide, longitudinal cracks in other parts of the beam. The high energy release was due to the high ultimate load sustained by the beam up to failure. Similar to Beams 5, 6 and 7, this beam had a small deflection at the ultimate load. Beam 3 had an ultimate deflection of 1.7 inches, compared with 1.6, 1.7 and 2.0 inches respectively for Beams 5, 6 and 7. All other beams had deflections of about 4 inches or larger at the ultimate load.

5.7 Strain Gage Measurements, Strain Distribution Measurements, and Deflection Measurements

Strain gages placed on the mild steel reinforcing bars, served to indicate where these bars were best utilized and to see what the behavior of these bars was under loading. Figure 4.3 gives a general layout of the locations of the strain gages. Turning to Appendix B and superimposing this diagram on the diagram of the beam, indicates the exact position of each gage on each particular reinforcing bar for each beam.

Figures 4.4(a) to (k) are plots of the moment on the beam (using the applied load per jack) versus the strain of the gage, for every

general location shown on Figure 4.3. Each beam having a gage at one of these general locations, has the gage's moment-strain relationship plotted on the overall graph of this general location.

A number of these gages were strained beyond their usable capacity during the testing of the beams. The plots for these are only up to their usable capacity.

The actual effectiveness of each reinforcing bar with a strain gage attached can be seen from these figures. For example, Figure 4.4(k) shows that the supplementary lower web reinforcing at the general location 'supplementary 3', produced approximately the same effect in both Beams 8 and 10.

Throughout testing, strain distribution measurements were taken from the Demec points located at the centerline of the beam, for each beam of this series. These readings gave the location of the neutral axis at each load increment. Figures 4.2(a), (b) and (c) show plots of these strain distribution measurements at various loading stages, for each beam in the test series.

The deflections for the beams which failed in shear, Beams 5, 6, 7, 3 and 4 were small and in the order of about 2 inches or less, except for Beam 4 which had an ultimate deflection of about 5 inches. This beam was stronger than the other four and sustained more deflection because its shear capacity was almost sufficient to force a flexural failure. However, as was noted by Nasser, Acavalos and Daniel[6], of the University of Saskatchewan, those beams containing web openings which failed in the flexural mode, namely Beams 2, 8, 9 and 10, all had larger ultimate deflections than Beam 1, the control beam, except

for Beam 10, which had a deflection of about 4 inches. This was probably due to a poorer quality of prestressing strands used. Comparisons can be made on Figures 4.1(a), (b) and (c). Greater deflection for the beams containing web openings is due to a decrease in stiffness of these beams produced by the web openings.

5.8 General Discussion

The shape of opening in this test series was the most important variable. The change from rectangular to parallelogram shaped openings, seems to have enabled these particular beams to behave more like the control beam with no openings. The combination of hole shape and type of loading and adequate shear reinforcing, in fact, enabled Beams 2, 8, 9 and 10 to reach their ultimate flexural strength and fail in the desired flexural mode. Assuming that the 11.8% decrease in total hole area between the rectangular and the parallelogram shaped web openings, did not contribute to the type of failure, then we can say that parallelogram shaped openings, or openings which allow the use of inclined shear stirrups, contribute highly to the overall strength of these beams.

In all cases where a shear failure occurred, it occurred through a hole section. Lower web reinforcing proved effective in increasing the ultimate load of the beam before a shear failure occurred, and also to produce a more ductile type of failure. This may be seen by comparing the behavior of Beams 5 and 7, and the failure in the lower web of Beams 3 and 4. Since the shear failures initiated in the flange and

upper web, above the hole sections in the shear spans of the beams, shear reinforcing in these locations would probably have enabled the beams to reach their ultimate flexural capacity, without failing in shear.

The type of loading, of course, influenced the type of failure, since the loading determined the bending and shear stresses at different locations along the beam. The combination of these stresses, when the shear stresses are severe enough, produces a shear or shear and combined bending type of failure.

The two point loading spaced at 12 feet centers for Beam 3, produced the most severe shear stresses to this beam. The other beams with the two point loading spaced at 8 feet centers, produced a less severe shear stress and probably one more similar to that which would occur if the beam was put to ordinary use. However, seven point loading is an even more realistic type of loading for the testing of these beams, since it comes the closest to approximating the shear and bending stresses produced by a uniformly distributed loading system, which is the most common type of loading found in practice. The beams in this series tested with a seven point loading, all failed in flexure, indicating that beams designed in this way are capable of reaching their ultimate flexural strength under a uniformly distributed load.

From the behavior of Beams 2 and 9, under a two point loading spaced at 8 feet centers, and Beams 8 and 10, under seven point loading spaced at 2 feet centers, it seems that a minimum spacing of shear reinforcing, and a minimum number of two stirrups per post, was adequate to enable Beams 9 and 10 to reach their ultimate flexural strength, the

same as their more highly reinforced counterparts, Beams 2 and 8. This indicates that only a minimum amount of shear reinforcing was required in the sections between the outside holes and the supports, and also in the posts in the shear spans.

Changing the prestress force by increasing or decreasing the number of prestressing strands in these beams, served to increase or decrease the ultimate flexural capacity of the beams and thus increase or decrease the amount of shear reinforcing necessary to prevent a shear failure from occurring, before the beam had reached its ultimate flexural capacity.

CHAPTER VI

SUMMARY, CONCLUSIONS, RECOMMENDATIONS

6.1 Summary

In this test series ten 24 foot long, prestressed concrete tee beams, simply supported on a 20 foot span were tested. The first beam was used as the control beam and contained no web openings, while three of the other nine beams contained rectangular openings and the other six beams contained parallelogram shaped web openings. The control beam, along with two of the beams containing parallelogram shaped openings, were tested under a seven point loading system, spaced at 2 feet centers, while the remaining seven beams were tested using a two point loading spaced at 8 feet centers, with one beam, Beam 3, tested with a two point loading system spaced at 12 feet centers. The prestress force of some of the beams of this series, was increased so as to increase the ultimate flexural capacity of these beams. This was achieved by increasing the number of 3/8 inch, 250k prestressing strands, from 4 strands to 5 strands. The stirrup spacing in the shear span of the beams, as well as the number of stirrups per post, was also used as a variable parameter. The results of the tests on these ten beams produced five shear, or shear and combined bending type failures, and five flexural type failures.

6.2 Conclusions

Based on the data and observations obtained from the tests of

these ten beams, each of which contained all or some of the previously mentioned independent variables, the following conclusions have been deduced.

a) Parallelogram shaped openings, accompanied by inclined shear stirrups, in prestressed concrete tee beams containing web openings, results in a beam with a higher ultimate capacity, relative to rectangular shaped openings and vertical shear stirrups, when the failure is a shear failure or a combined shear and bending type of failure.

b) As can be seen from the test results, the shear design requirements for a two point loading system are more severe than those for the seven point loading system.

c) An increase in the prestress force of a prestressed concrete tee beam with web openings, must also be accompanied by an increase in shear reinforcing, in order for the beam to attain its ultimate flexural strength without first failing in shear.

d) Since shear failures occur through the hole sections, shear reinforcing in the posts is not sufficient in itself, to prevent a shear failure.

e) Lower web reinforcing in the shear span below the web openings, increases the possibility of the beam to be able to withstand more severe shear stresses, and to ultimately fail in flexure. This reinforcing also produces a more ductile failure if the beam should fail in shear.

f) Upper web and flange shear reinforcing, above the hole sections in the shear spans, would probably increase the possibility of a flexural failure, in cases where the loading produces severe shear

stress conditions, since shear failures tend to initiate in the flange and upper web in this high shear stress region.

g) The ultimate load and moment calculated using the theoretical ACI Code procedure, in the case of flexural failure, is very conservative relative to the actual ultimate load and moment obtained from tests.

h) For those beams with web openings failing in flexure, the deflection at the ultimate load is higher than the same beam with no web openings, due to the decreased stiffness of the beam.*

6.3 Recommendations

a) Future investigations should consider maintaining a constant total hole area, while varying the shape and distribution of web openings.

b) Some form of shear reinforcing, that could be incorporated into the upper web and flange above the hole sections in the severe shear regions, should be investigated.

c) Further tests on these prestressed concrete tee beams should be carried out using 5 prestressing strands, since this increases the flexural capacity of the beam and places a higher demand on the shear reinforcing, in order for the beam to ultimately fail in flexure.

d) Tests should be carried out using draped prestressing strands. This would reduce the hole area in the shear span, where the influence

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*Compare Beam 2 with Sauve's control beam[8].

of web openings is most critical.

e) A further test on beams with parallelogram shaped openings, could include removing the central post of such beams, to increase the hole area in a theoretically non critical stress region.

f) Further investigations should concentrate on developing work already done in this test series, by taking a beam identical to one of this series and varying only one parameter.

g) Suggested variables for recommendation (f) are: (a) prestress force, and (b) upper web and flange reinforcing.

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REFERENCES

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APPENDIX A

MATERIALS AND PROCEDURES

APPENDIX A

A.1 Materials

a) Cement

Type III, high-early strength, Portland cement was used in all mixes.

b) Aggregate

The sand had a fineness modulus of 2.53 and an average moisture content of approximately 4%. The coarse aggregate used was a pea-gravel with a maximum size of 3/8 inch. Sieve analysis for the sand and coarse aggregate are presented in Tables A.1 and A.2. Both aggregates have been used in this laboratory for several previous investigations and have passed the usual specification tests.

c) Concrete Mix

A satisfactory mix design was used by Sauve[8]. The same mix design was adopted for this present test series. The ratios, by weight, per batch were:

Cement	1.0	(170 lb.)
Sand	2.2	(380 lb.)
Coarse aggregate	1.6	(270 lb.)
Water	0.39 to 0.51	(67 to 87 lb.)

The water/cement ratio was varied when necessary in order to maintain a minimum slump of 3 in., and at the same time to attain a strength bordering 5000 psi. A workable mix was required, due to congestion of reinforcement between and underneath each web opening.

Concrete cylinder strengths varying from 4689 to 6034 psi

were obtained; these figures were based on the average of two cylinder strengths per batch. A third cylinder per batch gave the splitting tensile strength, which varied from 248 to 580 psi. Table A.3 presents the age at test, compressive strength and the tensile concrete strength.

d) Prestressing Strand

The prestressing strand used in the test beams was 250k grade, 7-wire strand, with a 3/8 inch nominal diameter and complied with ASTM-A-416 Specifications. The elastic stress-strain diagram as obtained from a tensile test is shown in Figure A.1.

e) Shear Reinforcement

The stirrups were made from #3 deformed bars, bent to a specified shape by the supplier. The elastic stress-strain curve for this reinforcement is shown in Figure A.2. These curves were obtained from tensile tests conducted on a Baldwin Testing Machine. The strains were obtained from electrical resistance strain gages mounted on the bars. As shown in Figures 3.2(a) and (b), both 27 inch stirrups and 19 inch stirrups were used.

f) Longitudinal Reinforcement

The longitudinal reinforcement consisted of #3 deformed bars. The elastic stress-strain diagram of these is shown in Figure A.2.

A.2 Fabrication

a) Formwork

The forms used in this test program were in three sections,

each 8 feet long. They were slip type forms of 3/4 inch and 1/2 inch plywood, with timber battens to maintain rigidity under the pressure of the fresh concrete. Figure A.3 shows a cross-section of the forms at an opening. Styrofoam shaping blocks were fitted into the interior forms. By simply changing interior forms and styrofoam block shape, a different shape of opening could be provided. In this series, as already stated, two types of hole patterns were used. There was no mechanical connection between the exterior and interior forms. The exterior forms were, however, bolted to a steel channel base. An overall view of the formwork is shown in Figure A.5.

After the concrete had set for 24 hours, the exterior forms were unbolted and slipped off, while the interior forms were peeled off the hardened concrete. The styrofoam blocks were then punched through.

b) <u>Prestressing Operation</u>

The prefabricated shear reinforcement cages were laid on the base of the formwork with one side removed for accessibility. High strength prestressing cables were then threaded through the prestressing abutments, form end-plates and through the shear cages. At one end of the beam, prefabricated steel dynamometers were slipped on the strands and CCL anchoring devices were then used to grip the cables. Prefabricated concrete-steel abutments were used to resist the tension forces of the prestressed strands.

Each strand was tensioned individually using a simplex center hole hydraulic jack, operated by an electrically driven Blackhawk pump. The correct tensioning loads were obtained by reading the strains of the dynamometers. Strains were measured by electrical resistance

strain gages mounted on the dynamometers. When the correct prestress was reached, a CCL grip, located between the jack and the abutments was pushed snug to the abutment back-plate; the jack was then released and removed. After all the strands were tensioned, the form side was erected, adjusted for alignment and then four steel wood clamps were placed along the top of the forms to maintain a correct flange width.

c) Casting and Curing

The concrete was mixed in a nine cubic foot vertical drum mixer. Each beam required three batches except for Beam 1, which required four. The concrete was compacted using an electric immersion type vibrator. Compaction control was carefully supervised so that no air pockets formed beneath the styrofoam blocks. For each batch of concrete, three 6 x 12 inch control cylinders were cast; two were tested in compression and one in splitting.

Immediately after casting and finishing, each beam was covered by a damp-proof sheet in an attempt to minimize early shrinkage cracking, and to promote curing. After a 24 hour period the side forms were removed and the beams were then enclosed in a saturated burlap and then covered by a damp-proof sheet. A humid atmosphere was maintained for six days prior to the release of the strands. The control cylinders were always subjected to the same curing conditions as the beams. After release of the strands, the beams were stored in the laboratory atmosphere for periods of from 21 to 29 days before testing.

d) Release of Prestress

The prestress was released in all of the beams, 6 days after casting. The first stage in the release was to cut the strands at one

end of the beam. This was accomplished by gently applying heat from an oxy-acetylene flame, over a length of about four feet between the stopend and the abutment, until the individual strands broke. Fracture was always gentle indicating that a uniform transfer of prestress had resulted.

A.3 Prestress Losses

A complete set of Demec strain gage readings was taken immediately before and after release, and these were used, together with the initial readings taken at the beginning of each test, to calculate losses of strain in the beam and strands.

Losses which occurred during the prestressing operation, due to anchorage slip and to release of the jack, all took place before the initial prestress was calculated. Therefore, the losses which are presented under the "Total Loss" heading in Table A.4 refer to elastic, creep and shrinkage losses in the concrete, and to relaxation in the steel.

The initial prestress forces in the strands were calculated from the dynamometer readings taken immediately before release.

A.4 Loading Apparatus

A seven point loading system as well as a two point loading system were used in this test series. In every case, loading was through the floor by means of a harness. This harness was seated across the flange of the beam, two steel rods passed through the

loading floor and jacks were mounted on the lower portion of the harness and pushed against the basement ceiling. Each harness consisted of: two eight foot high strength steel rods, as well as two 4 x 4 x 1/4 inch hollow, structural steel tubes. The jack was fastened to the lower tube under the floor and the upper tube was laid transversely on the flange of the beam. The two tubes being connected on either side of the flange by an 8 foot long steel rod. A typical cross-section of this loading set up is shown in Figure A.6. For seven point loading, seven 10 ton jacks were used and for the two point loading two 30 ton jacks were used. In each case, these were securely fastened to the harness. Each jack was hooked up with a rubber hose, which in turn was fastened to a manifold. The manifold was hooked up to the Amsler hydraulic pump. The loading frame is shown in Figure A.4. During each increment of loading the load was maintained manually.

Point loading along the longitudinal centerline of the flange of the beam, was achieved by placing 4 x 6 x 1/2 inch steel plates under the hollow structural steel tube, at the exact centerline and exact transverse location along the beam. Plaster of Paris was used to hold the plates in place. Both supports were hinged so as to permit rotation; one of the supports was longitudinally fixed, and the other was mounted on rollers to permit simple beam action.

TABLE A.1

SIEVE ANALYSIS OF SAND

SIEVE SIZE	WEIGHT RETAINED (GMS)	% RETAINED	CUMULATIVE % RETAINED	A.S.T.M. STANDARD
#4	17.5	3.0	3.0	0-5
#8	85.2	14.7	17.7	-
#16	54.6	9.5	27.2	20-55
#30	60.0	10.3	37.5	-
#50	208.4	35.8	73.3	70-90
#100	122.9	21.1	94.4	90-98
PAN	17.8	3.1	-	-
SILT	14.4	2.5	-	-
TOTAL	580.8	100.0		
FINENESS MODULUS		2.53		

TABLE A.2

SIEVE ANALYSIS OF COARSE AGGREGATE

SIEVE SIZE	% RETAINED	CUMULATIVE % RETAINED
3/4	0	0
3/8	5.9	5.9
#4	87.1	93.0
PAN	7.0	100.0
TOTAL	100.0	

TABLE A.3

SUMMARY OF CONCRETE STRENGTHS

BEAM NO.	MIX NO.	AGE AT TEST (DAYS)	AVGE. CYLINDER STRENGTH (psi)	SPLITTING STRENGTH psi
1	I	21	5538	292
	II		5618	469
	III		4689	350
	IV		5016	420
2	I	23	5104	372
	II		5803	434
	III		4830	367
3	I	23	5370	310
	II		5396	350
	III		5211	394
4	I	23	5113	301
	II		5715	332
	III		5078	389
5	I	29	5325	389
	II		5113	372
	III		4918	363
6	I	29	4874	372
	II		5007	372
	III		5051	363
7	I	26	4759	248
	II		5202	354
	III		5042	327
8	I	22	4733	372
	II		5361	407
	III		5166	385
9	I	22	5635	398
	II		5369	372
	III		4892	332
10	I	23	5821	425
	II		5458	473
	III		6034	580

TABLE A.4

SUMMARY OF PRESTRESS LOSSES

BEAM NO.	INITIAL PRESTRESS (ksi)	ELASTIC LOSS (ksi)	TIME LOSS* (ksi)	TOTAL LOSS (ksi)	Pe** (ksi)
1	167	13.5	12.0	25.5	141.5
2	169	15.6	18.9	34.5	134.5
3	167	15.3	24.0	39.3	127.7
4	168	23.4	32.7	56.1	111.9
5	167	23.4	30.6	54.0	113.0
6	168	25.5	30.6	56.1	111.9
7	167	25.5	34.5	60.0	107.0
8	172	25.5	14.1	39.6	132.4
9	173	12.3	24.6	36.9	136.1
10	170	24.3	17.7	42.0	128.0

* Measured from time of transfer to time of testing.

** Effective Prestress

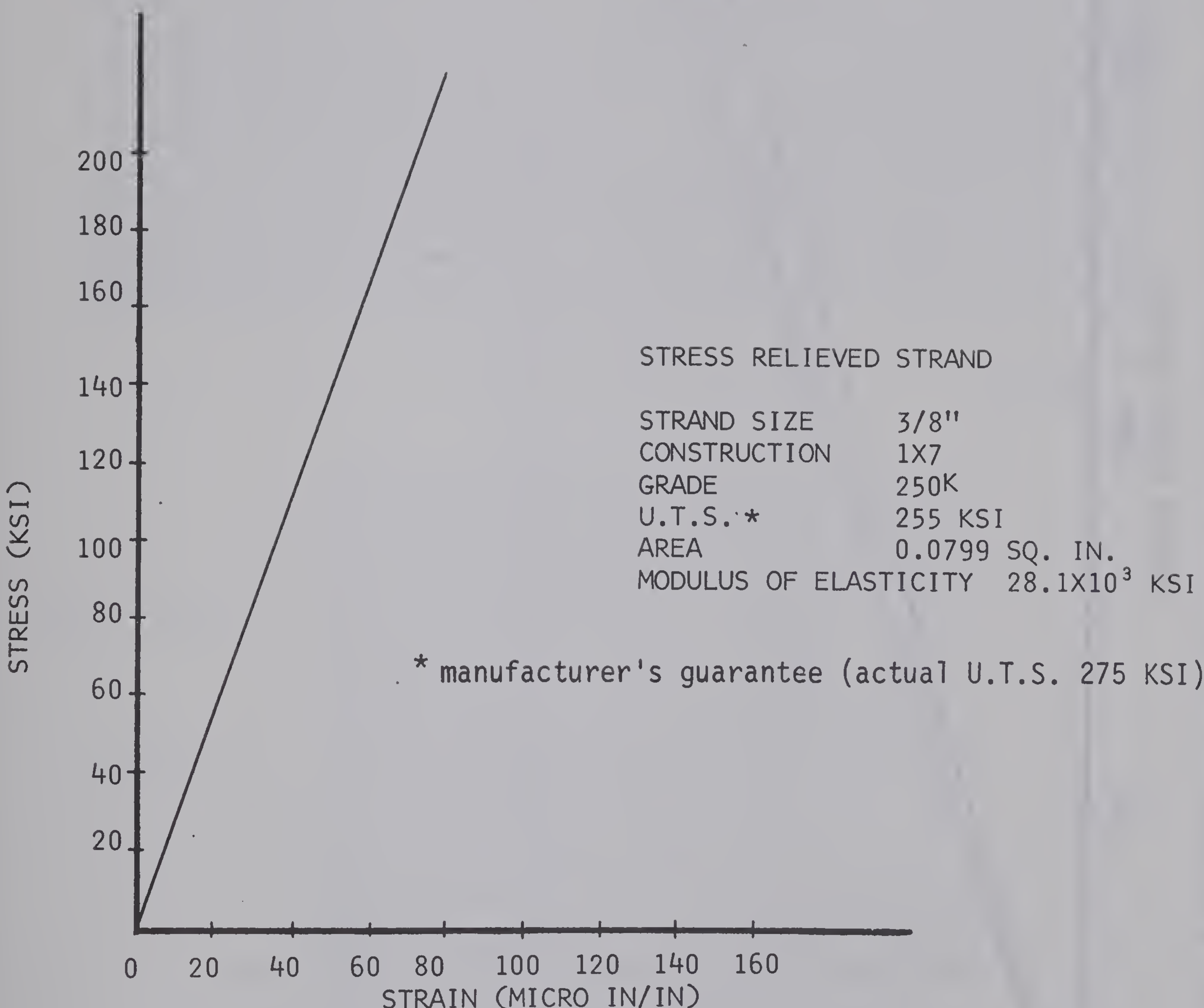


FIGURE A.1 STRESS-STRAIN RELATIONSHIP OF PRESTRESSING STRAND

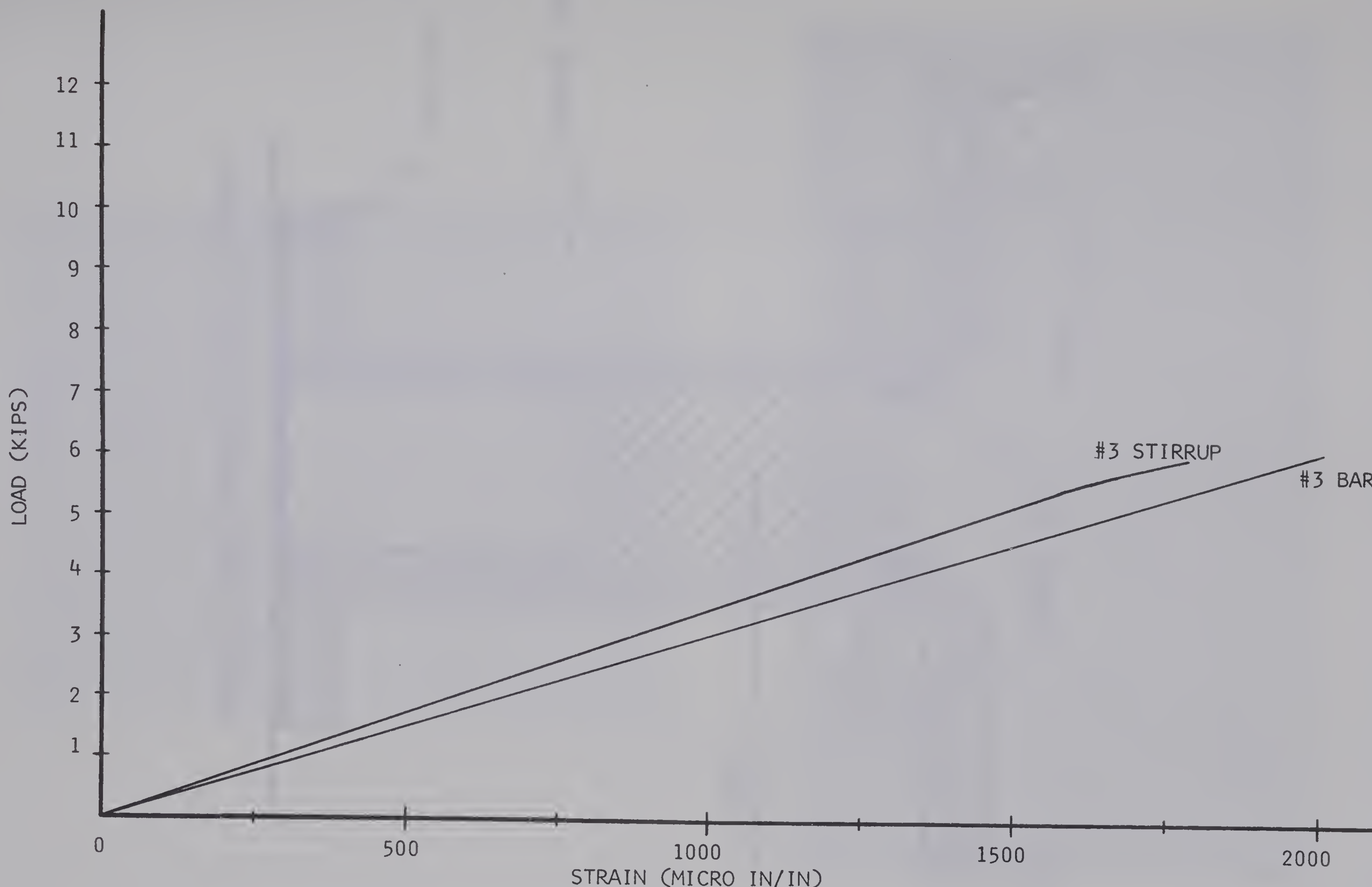


FIGURE A.2 LOAD-STRAIN RELATIONSHIP FOR VERTICAL AND LONGITUDINAL REINFORCEMENT

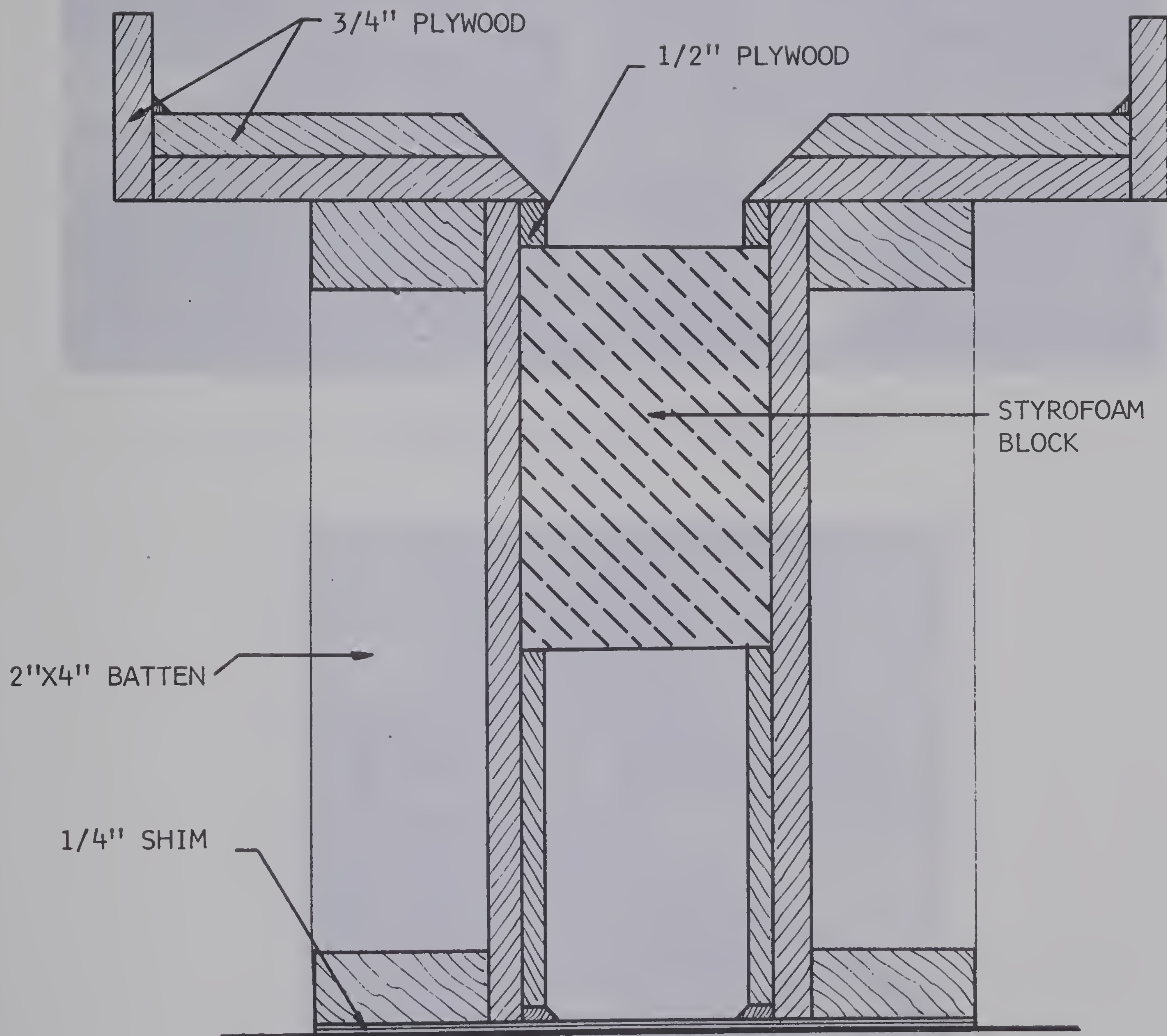


FIGURE A.3 TYPICAL X-SECTION THROUGH FORMWORK

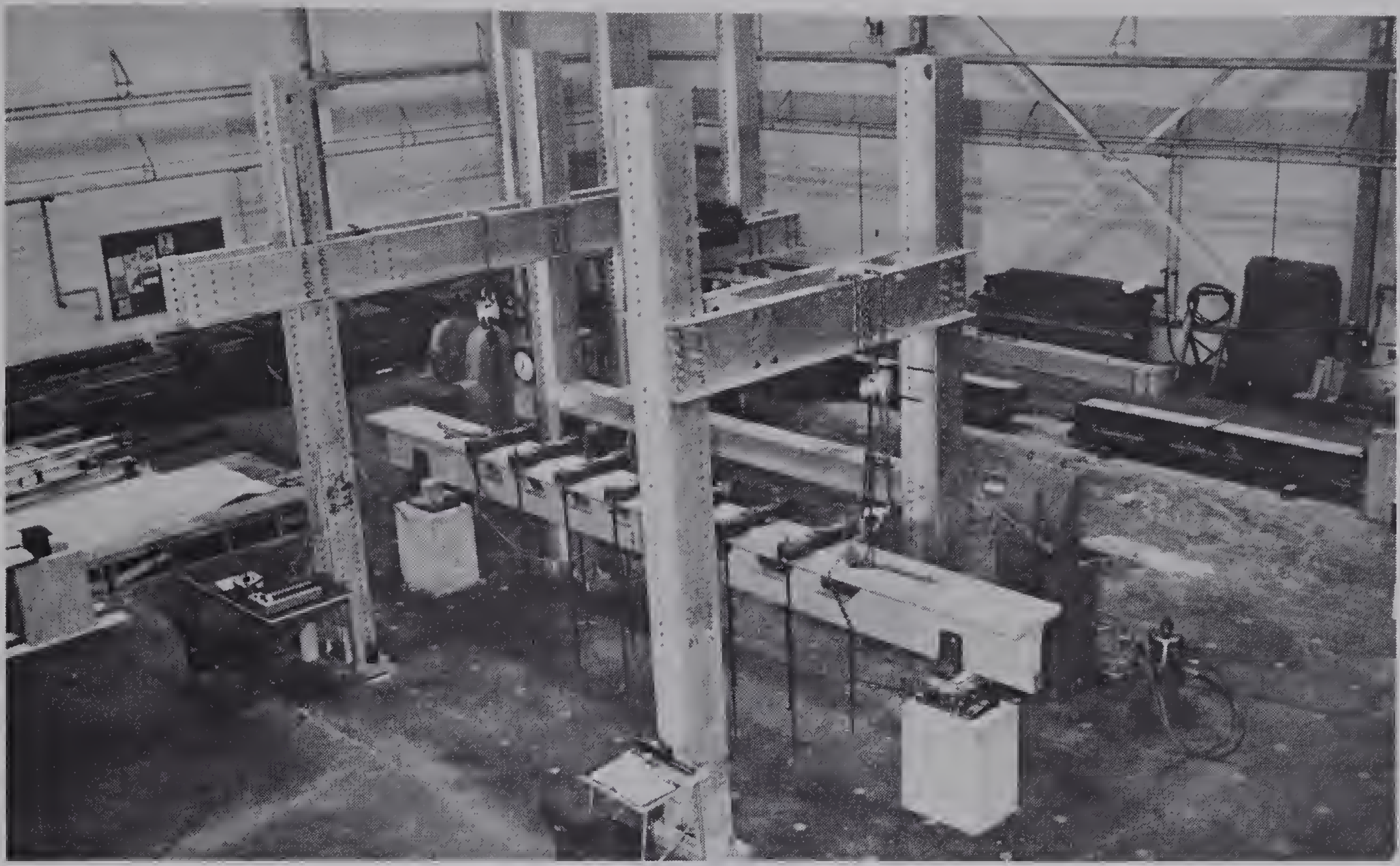


FIGURE A.4 TYPICAL TEST SET-UP

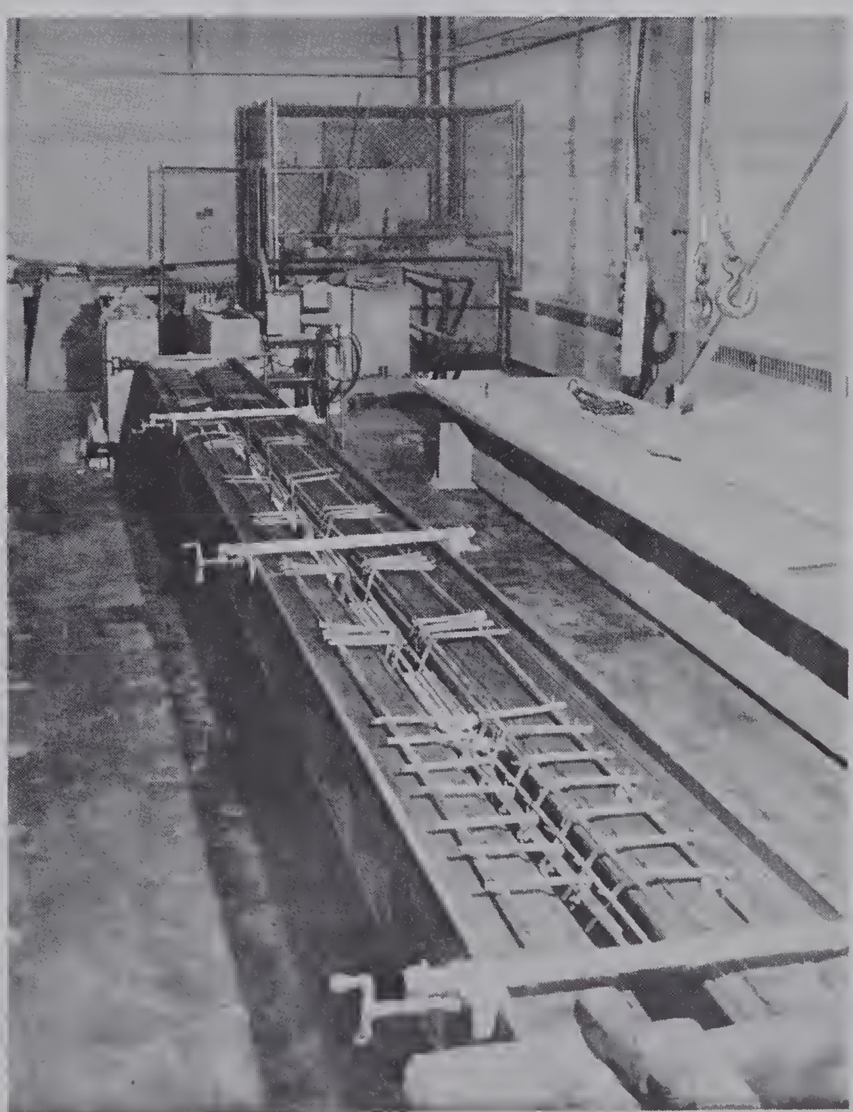


FIGURE A.5 FORMWORK

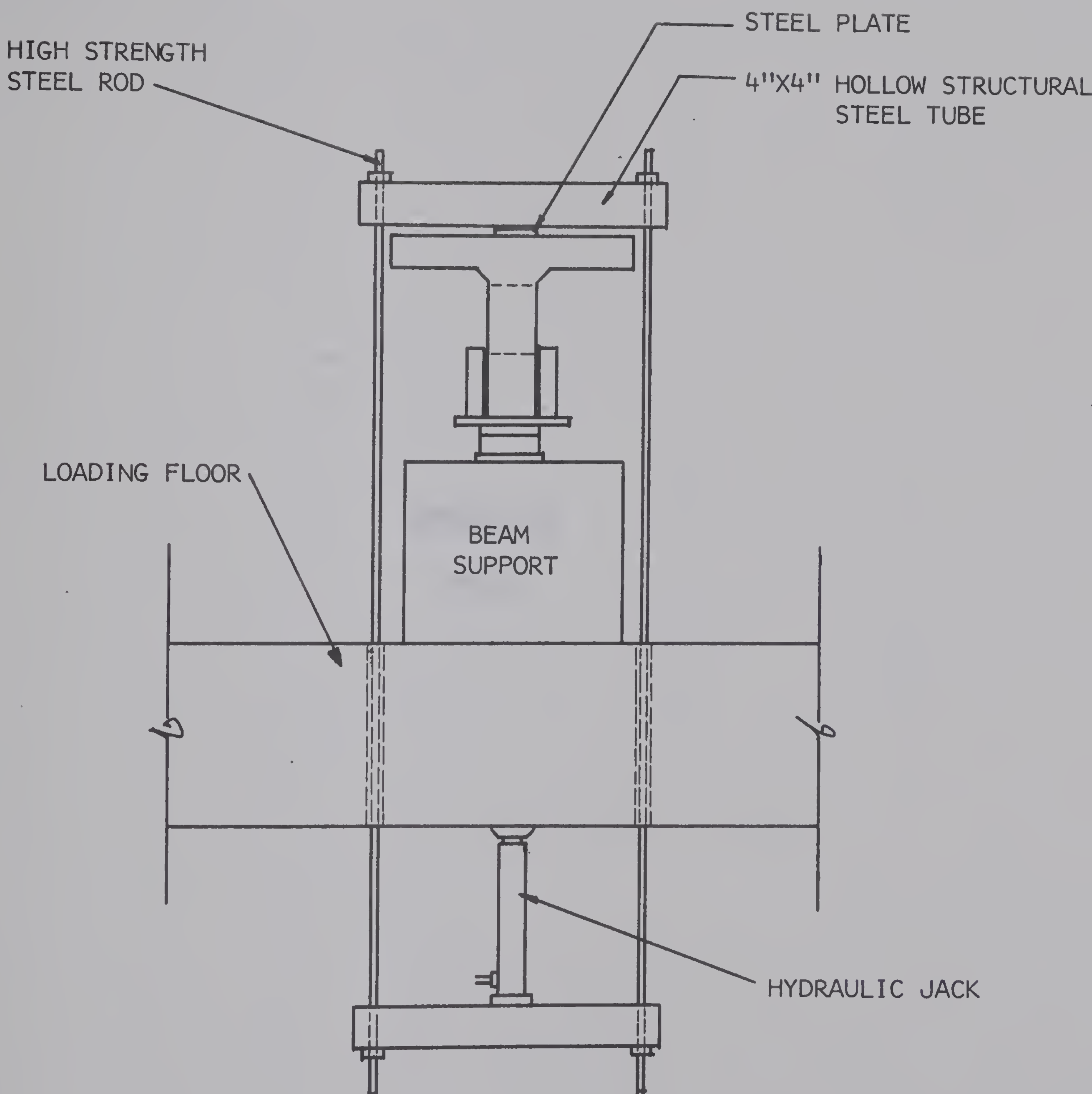
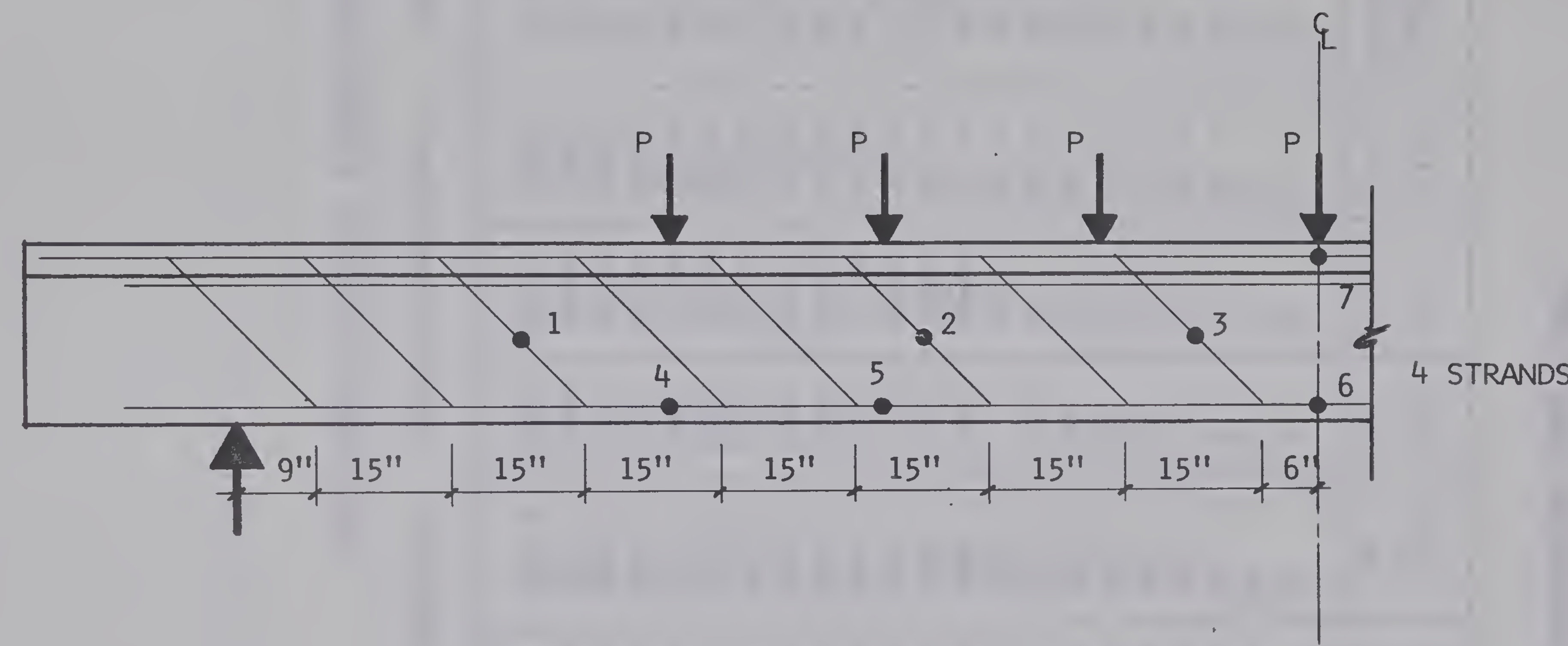


FIGURE A.6 TYPICAL X-SECTION OF LOADING HARNESS

APPENDIX B

DATA

The data supplied in this Appendix contains reinforcement details and strain gage locations, strain gage measurements, Demec point measurements, deflections, and load deflection diagrams, for each beam of the test series.



REINRORCEMENT DETAIL
STRAIN GAGE LOCATIONS
BEAM 1

FIGURE B.1.1 BEAM 1

TABLE B.1.1

STRAIN GAGE MEASUREMENTS

LOAD (kips)	(1) **	(2) **	(3) **	(4) **	(5) **	(6) **	(7) **
0	0	0	0	0	0	0	0
.2	0	0	0	+ 8*	+ 12	+ 15	- 5
.6	+ 4	- 8	- 5	+ 50	+ 80	+ 104	- 240
1.0	+ 10	- 15	- 12	+ 90	+ 135	+ 178	- 376
1.4	+ 18	- 20	- 40	+ 148	+ 225	+ 308	- 675
1.8	+ 26	- 20	- 65	+ 196	+ 312	+ 460	- 920
2.2	+ 34	- 18	- 80	+ 252	+ 426	+ 665	-1110
2.6	+ 46	- 6	- 62	+ 315	+ 568	+ 988	-1290
3.0	+ 56	+ 15	- 4	+ 385	+ 840	+1492	-1416
3.4	+ 75	+205	+ 60	+ 466	+1212	+2102	-1520
3.8	+ 96	+480	+112	+ 560	+1580	+2685	-1600
4.2	+120	+735	+156	+ 750	+1930	+3078	-1662
4.4	+136	+812	+218	+ 890	+2204	+3112	-1700
4.6	+154	+860	+305	+ 980	+2420	+3158	-1735
5.0	+184	+1022	+470	+1220	+2676	+3020	-1784
5.2	+210	+188	+588	+1346	+2716	+2838	-1824
5.4	+230	+320	+708	+1450	+2730		-1840
5.6	-938	+270	-344	+ 478	+1534		-3040
5.8	-914	+410	-195	+ 564	+1554		-3030
6.0	-890	+534	- 74	+ 640	+1570		-2910
6.2	-860	+644	+300	+ 720	+1578		-2700
6.4	-830	+730	+486	+ 770	+1605		-2526

*NOTE: + indicates tension; - indicates compression

**Measurements in micro inches/inch

TABLE B.1.2

DEMEC POINT MEASUREMENTS

LOAD (kips)	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
i	0	0	0	0	0	0	0	0	0
ii	- 40*	- 36	- 28	- 16	- 4	+ 6	+ 6	+ 5	+ 9
0	- 90	- 70	- 51	- 32	- 20	- 15	- 14	- 16	- 17
0.1	- 88	- 70	- 49	- 32	- 24	- 21	- 22	- 20	- 25
0.4	- 83	- 67	- 52	- 37	- 28	- 22	- 24	- 22	- 29
0.8	- 75	- 63	- 51	- 43	- 32	- 24	- 28	- 28	- 32
1.2	- 59	- 61	- 54	- 57	- 35	- 28	- 29	- 27	- 35
1.6	- 59	- 60	- 58	- 73	- 39	- 30	- 31	- 29	- 37
2.0	- 44	- 52	- 58	- 86	- 44	- 38	- 42	- 37	- 39
2.4	- 25	- 38	- 53	- 93	- 48	- 48	- 50	- 40	- 43
2.8	+ 4	- 2	- 28	- 88	- 53	- 55	- 56	- 50	- 47
3.2	+ 40	+ 40	+ 2	- 76	- 53	- 62	- 70	- 54	- 53
3.6	+ 90	+ 92	+ 40	- 58	- 52	- 71	- 72	- 68	- 69
3.8	+103	+116	+ 58	- 49	- 40	- 80	- 81	- 79	- 80
4.0	+136	+141	+ 76	- 37	- 32	- 87	- 90	- 88	- 89
4.2	+156	+164	+ 93	- 29	- 20	- 94	- 94	- 92	- 93
4.4	+193	+208	+127	- 5	- 17	-111	-105	-110	-110
4.6	+243	+260	+165	+ 20	+ 2	-120	-115	-116	-117
4.8	+298	+314	+207	+ 47	+ 9	-131	-126	-129	-130
5.0	+382	+394	+268	+ 88	+ 29	-142	-139	-137	-140
5.2	+545	+538	+382	+161	+ 50	-150	-145	-150	-149
5.4	+657	+628	+463	+216	+ 79	-159	-157	-157	-155
5.6	+839	+781	+494	+299	+100	-167	-163	-162	-170
5.8	+1120	+1038	+806	+330	+115	-178	-170	-169	-175
6.4	failure								

i indicates before transfer

ii indicates after transfer

*NOTE: x 10^{-4} inches (+ tension, - compression)

TABLE B.1.3

DEFLECTIONS

LOAD (kips)	SOUTH * (in)	℄ (in)	NORTH * (in)
0	0	0	0
0.1	0	0	0
0.4	.03	.04	.03
0.8	.05	.07	.07
1.2	.13	.17	.12
1.6	.19	.25	.21
1.8	.22	.29	.24
2.0	.25	.33	.28
2.2	.28	.38	.32
2.4	.32	.41	.34
2.6	.35	.46	.39
2.8	.40	.53	.43
3.0	.44	.60	.49
3.2	.51	.68	.55
3.4	.58	.79	.64
3.8	.72	.96	.78
4.2	.84	1.13	.97
4.6	1.05	1.41	1.13
5.0	1.28	1.75	1.39
5.4	1.71	2.34	1.81
5.8	2.24	3.11	2.39
6.2	3.40	4.81	3.39
6.4	4.38	6.06	4.49

* indicates 1/3 points

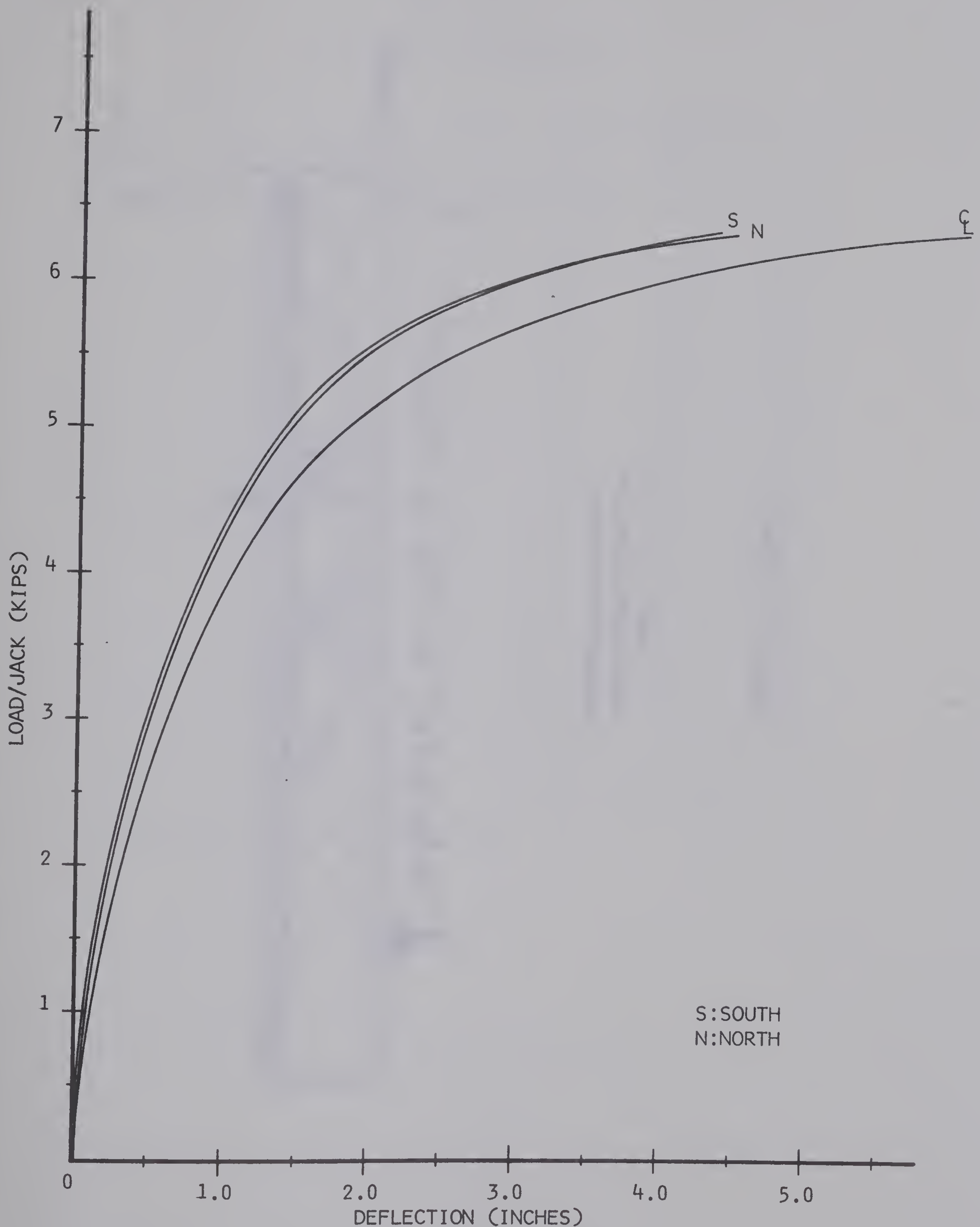
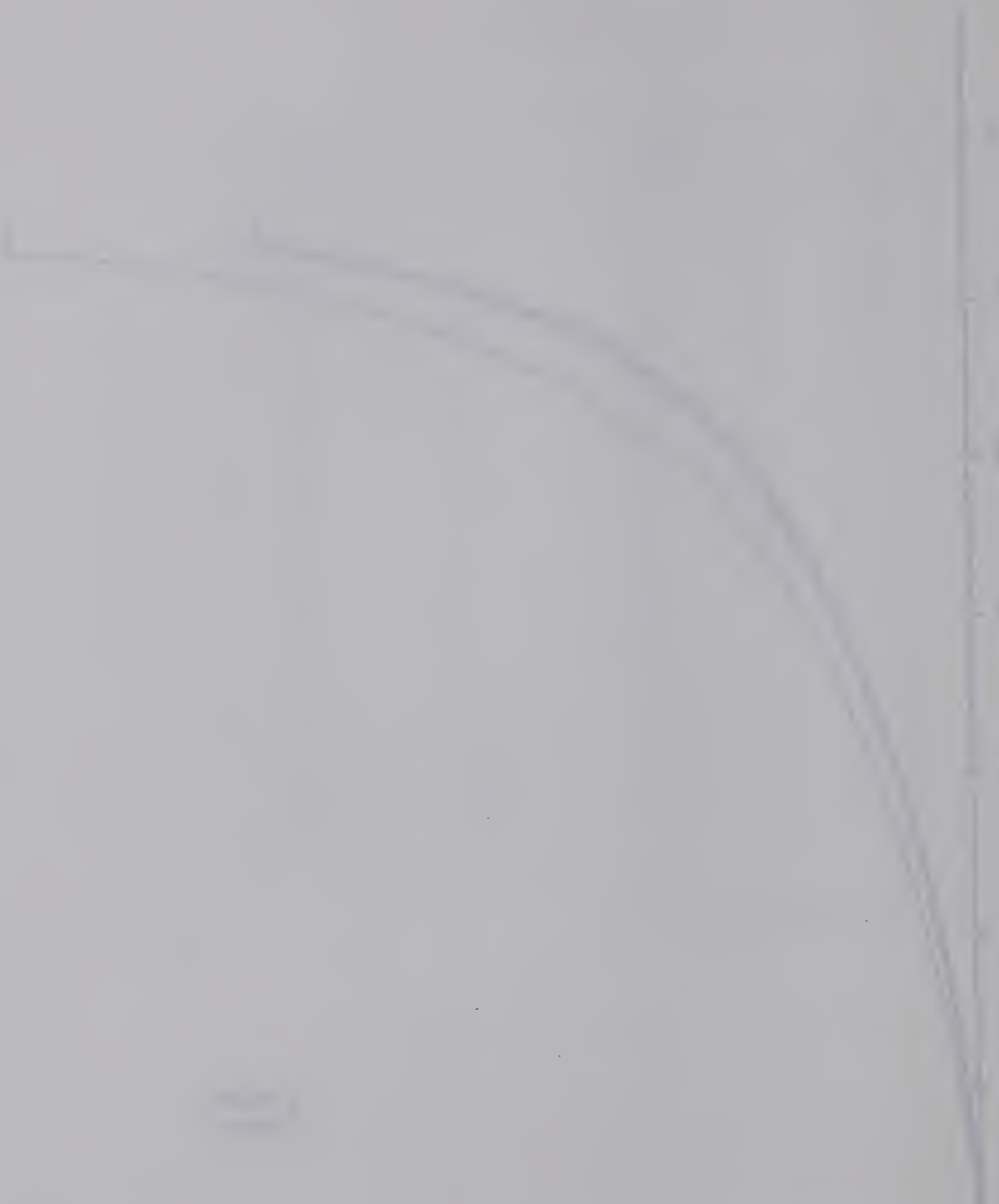
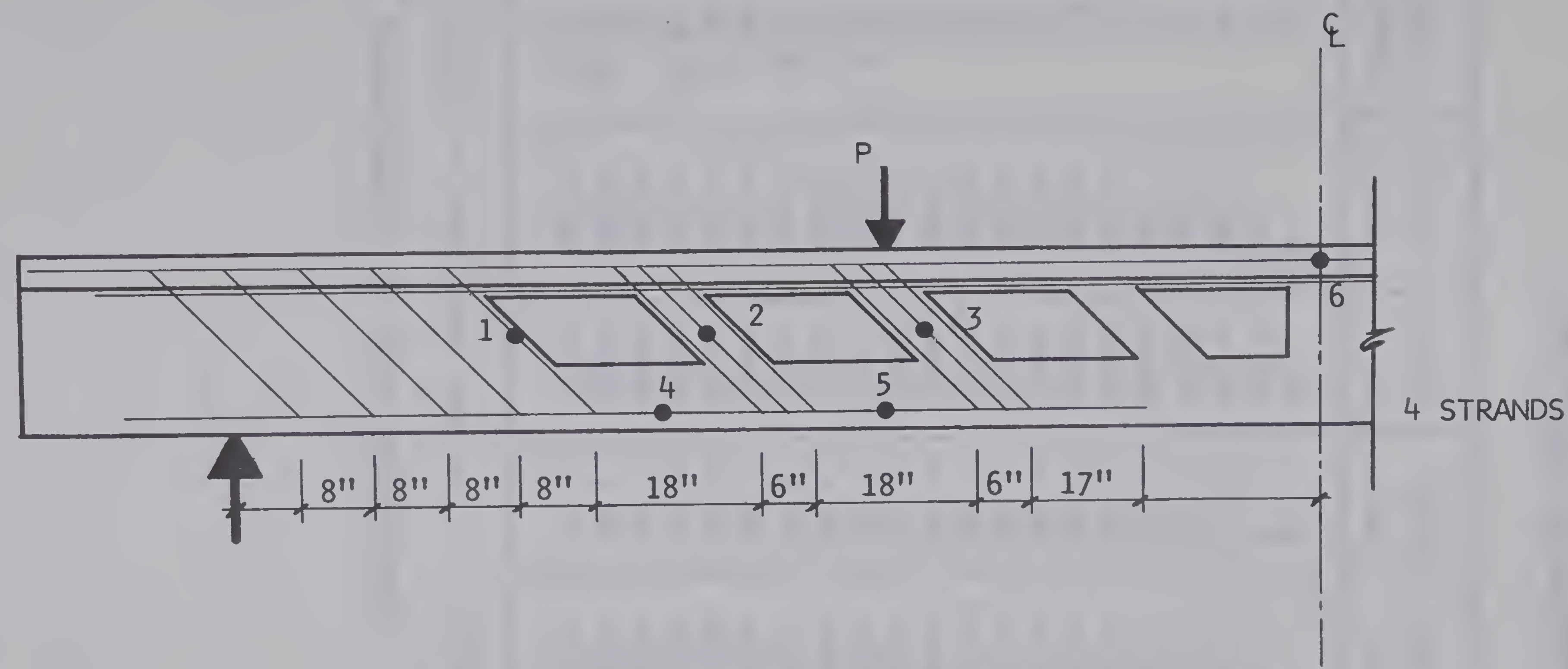


FIGURE B.1.2 LOAD-DEFLECTION DIAGRAM,BEAM 1





REINFORCEMENT DETAIL
STRAIN GAGE LOCATIONS
BEAM 2

FIGURE B.2.1 BEAM 2

TABLE B.2.1

STRAIN GAGE MEASUREMENTS

LOAD (kips)	(1) **	(2) **	(3) **	(4) **	(5) **	(6) **
0	0	0	0	0	0	0
2	+ 34*	+ 28	+ 5	+ 56	+ 90	- 40
4	+ 106	+ 78	+ 10	+ 118	+ 200	- 85
6	+ 336	+256	+ 22	+ 182	+ 320	-130
8	+ 624	+448	+ 32	+ 236	+ 456	-166
10	+ 900	+606	+ 48	+ 300	+ 964	-210
11	+1012	+666	+ 50	+ 346	+ 1364	-234
12	+1132	+680	+ 48	+ 392	+ 1634	-244
13	+1244	+692	+ 58	+ 440	+ 1936	-250
14	+1378	+710	+ 68	+ 705	+ 2366	-250
15	+1450	+742	+ 54	+ 930	+ 2740	-250
16	+1544	+790	+ 58	+1295	+ 2968	-240
16.5	+1570	+798	+ 70	+1420	+ 2980	-230
17	+1606	+822	+ 76	+1582	+11930	-210
17.5	+1652	+832	+ 98	+1756	+13384	-180
18	+1676	+846	+100	+1892	+14200	-130
18.5	+1716	+875	+100	+2094	+16150	+ 18
18.75	+1748	+885	+ 96	+2180	+16960	+140
19	+1784	+898	+ 94	+2282	+17704	+315
19.25	+1805	+908	+ 92	+2348	+18146	+442
19.5	+1844	+930	+ 84	+2498	+19005	+824

* NOTE: + indicates tension; - indicates compression

** Measurements in micro inches/inch

TABLE B.2.2

DEMEC POINT MEASUREMENTS

LOAD (kips)	(1)	(2)	(3)	(5)	(6)	(7)	(8)	(9)
i	0	0	0	0	0	0	0	0
ii	- 55*	-41	- 46	- 7	+ 7	+ 5	+ 6	+ 7
0	- 115	-91	-100	-59	- 40	- 33	- 47	- 53
1	- 107	-87	- 91	-58	- 41	- 35	- 50	- 52
2	- 104	-85	- 91	-56	- 44	- 38	- 46	- 54
3	- 105	-87	- 93	-54	- 44	- 39	- 51	- 57
4	- 100	-84	- 81	-54	- 46	- 31	- 53	- 58
5	- 90	-72	- 78	-53	- 47	- 44	- 55	- 60
6	- 88	-70	- 82	-52	- 50	- 48	- 60	- 60
7	- 76	-64	- 71	-52	- 54	- 50	- 60	- 70
8	- 73	-62	- 69	-52	- 57	- 57	- 68	- 72
9	- 68	-56	- 68	-56	- 58	- 57	- 71	- 73
10	- 63	-56	- 58	-55	- 59	- 59	- 74	- 75
10.5	- 57	-45	- 53	-56	- 61	- 61	- 74	- 86
11	+ 27	-53	+ 17	-48	- 69	- 72	- 86	- 92
11.5	+ 53	-56	+111	-45	- 75	- 76	- 91	- 95
12	+ 89	-54	+154	-40	- 76	- 79	- 94	- 99
12.5	+ 133	-50	+206	-39	- 83	- 83	- 98	-103
13	+ 181	-54	+152	-36	- 83	- 87	-101	-110
13.5	+ 270	-53	+213	-36	- 88	- 92	-107	-117
14	+ 363	-62	+379	-28	- 96	- 99	-116	-120
14.5	+ 478	-64	+444	-28	-100	-103	-118	-127
15	+ 716	-68	+494	-18	-103	-111	-127	-137
15.5	+ 991	-78	+584	-10	-102	-117	-133	-164
16	+1281	-72	+690	+ 5	-122	-125	-141	-155
16.5	+1744	-69	+764	+14	-131	-136	-151	-164
17	+2400	-74	+884	+27	-139	-144	-160	-185
19.5	failure							

i indicates before transfer

ii indicates after transfer

*NOTE: x 10^{-4} inches (+ tension, - compression)

TABLE B.2.3

DEFLECTIONS

LOAD (kips)	SOUTH * (in)	℄ (in)	NORTH * (in)
0	0	0	0
2.0	.04	.05	.03
4.0	.09	.11	.08
6.0	.14	.17	.12
8.0	.20	.24	.19
10.0	.28	.33	.26
10.5	.29	.37	.30
11.0	.39	.47	.37
11.5	.45	.58	.47
12.0	.52	.64	.53
12.5	.57	.73	.58
13.0	.64	.79	.63
13.5	.73	.91	.72
14.0	.82	1.04	.82
14.5	.90	1.14	.90
15.0	.98	1.26	.99
15.5	1.13	1.44	1.12
16.0	1.29	1.65	1.30
16.5	1.45	1.86	1.43
17.0	1.64	2.11	1.65
17.5	2.03	2.59	2.04
18.0	2.30	3.04	2.35
18.5	3.08	3.99	3.09
19.0	4.04	5.37	4.05
19.5	6.85	8.59	6.65

* indicates 1/3 points

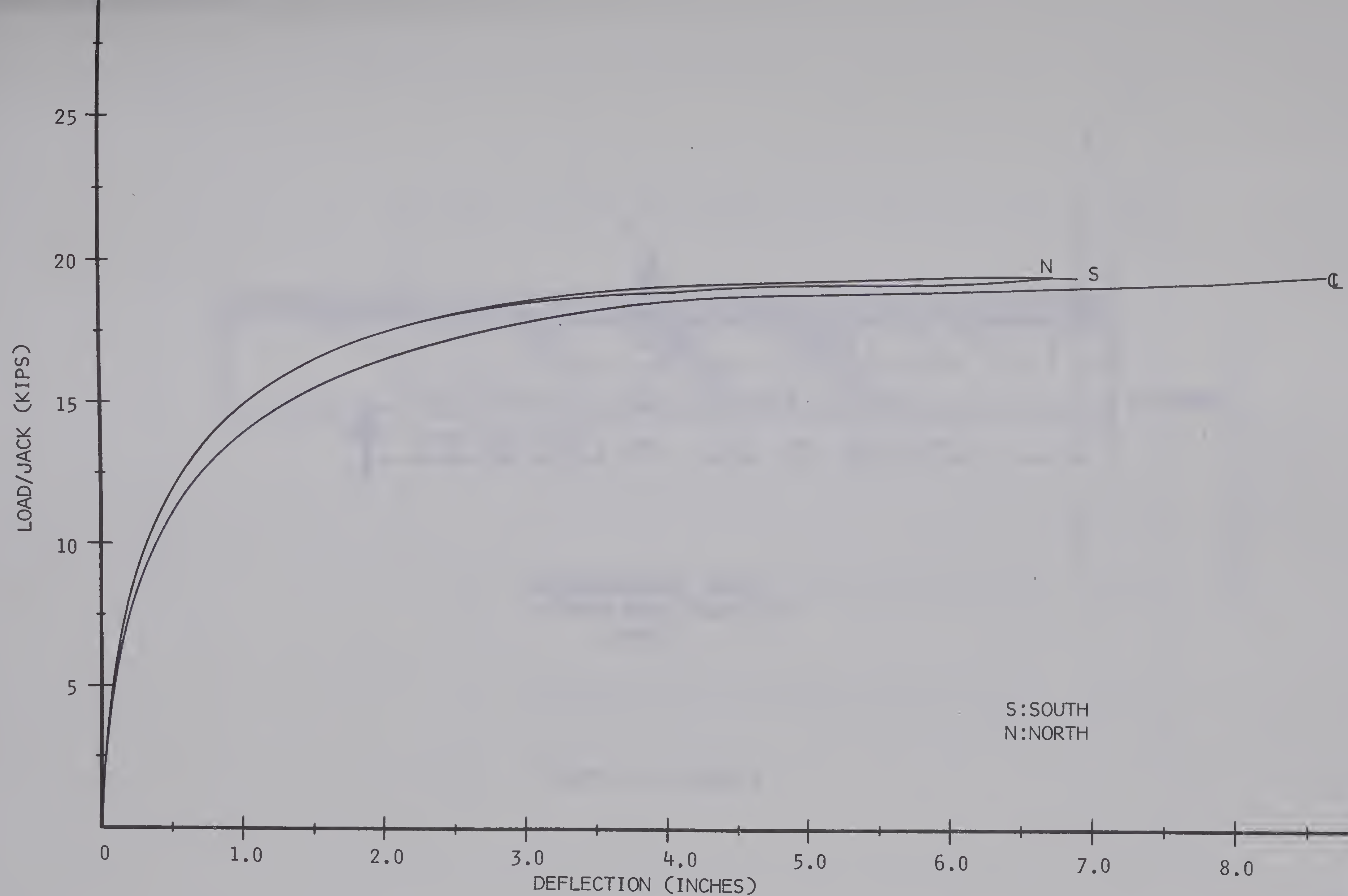
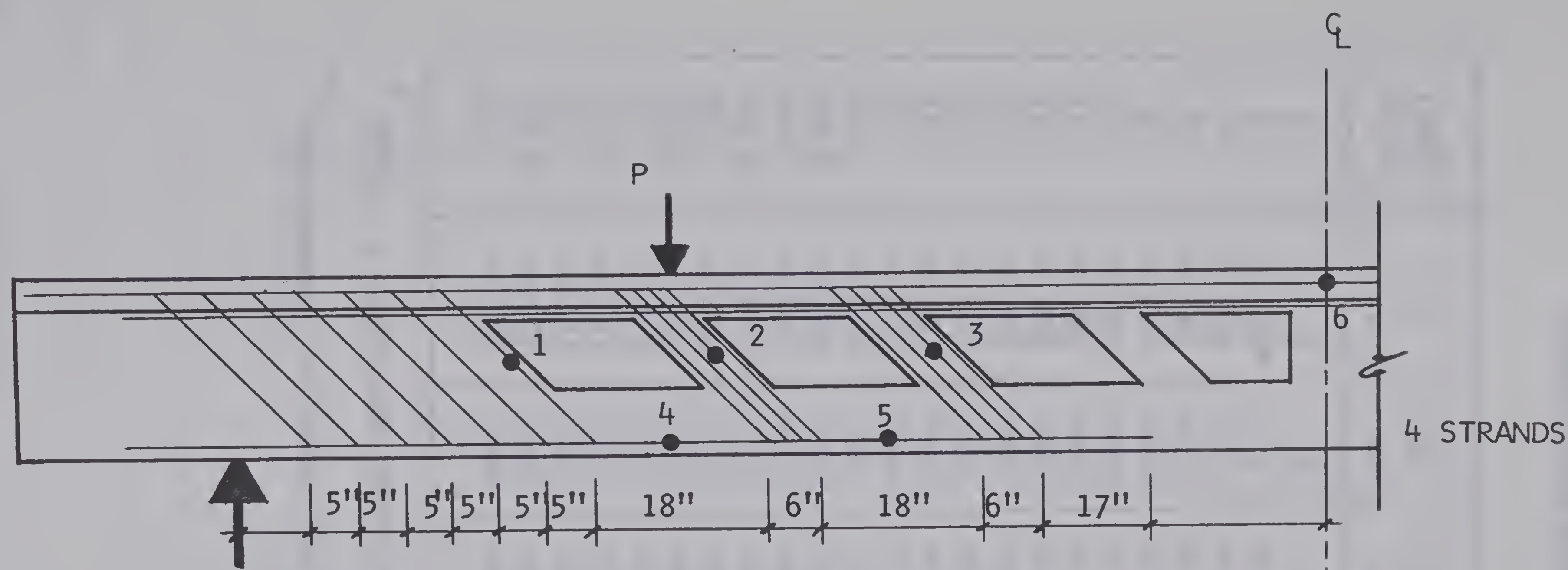


FIGURE B.2.2 LOAD-DEFLECTION DIAGRAM,BEAM 2



REINFORCEMENT DETAIL
STRAIN GAGE LOCATIONS
BEAM 3

FIGURE B.3.1 BEAM 3

TABLE B.3.1

STRAIN GAGE MEASUREMENTS

LOAD (kips)	(1) **	(2) **	(3) **	(4) **	(5) **
0	0	0	0	0	0
2	+ 32*	+ 7	+ 2	+ 56	+ 44
4	+ 104	+14	+ 1	+ 132	+ 100
6	+ 193	+23	+ 2	+ 210	+ 160
8	+ 280	+33	+ 2	+ 282	+ 212
10	+ 308	+53	+ 5	+ 387	+ 280
12	+ 383	+66	+ 7	+ 710	+ 357
13	+ 410	+67	+ 9	+ 901	+ 397
14	+ 459	+67	+10	+1120	+ 454
15	+ 514	+63	+10	+1257	+ 512
16	+ 581	+58	+ 9	+1491	+ 926
17	+ 610	+44	+15	+1651	+1207
18	+ 874	+30	+16	+1834	+1404
18.5	+ 937	+27	+20	+1949	+1506
19	+ 956	+35	+36	+2090	+1726
19.5	+ 992	+26	+30	+2174	+1845
20	+1008	+26	+34	+2254	+1967
20.5	+1044	+24	+46	+2363	+2118
21	+1078	+22	+50	+2487	+2264
21.5	+1117	+21	+52	+2590	+2392
22	+1164	+20	+52	+2685	+2508
22.5	+1572	+50	+50	+2875	+2663
23	+1622	+48	+46	+2866	+2839

* NOTE: + indicates tension; - indicates compression

** Measurements in micro inches/inch

TABLE B.3.2

DEMEC POINT MEASUREMENTS

LOAD (kips)	(1)	(2)	(3)	(5)	(6)	(7)	(8)	(9)
i	0	0	0	0	0	0	0	0
ii	- 52*	- 44	- 24	0	+ 4	+ 5	+ 5	+ 3
0	-131	-107	-140	-49	- 41	- 38	- 38	- 33
1	-124	-110	-141	-53	- 38	- 38	- 31	- 33
2	-121	-106	-137	-56	- 40	- 41	- 30	- 35
3	-117	- 98	-143	-55	- 46	- 32	- 42	- 37
4	-115	-103	-144	-52	- 45	- 44	- 42	- 38
5	-113	- 95	-146	-57	- 45	- 45	- 44	- 40
6	-105	- 92	-150	-60	- 41	- 47	- 46	- 42
7	-110	- 91	-150	-61	- 51	- 49	- 50	- 45
8	-106	- 93	-150	-67	- 52	- 50	- 50	- 46
9	-101	- 87	-153	-60	- 53	- 53	- 53	- 49
10	- 96	- 77	-164	-56	- 54	- 55	- 55	- 51
11	- 94	- 85	-166	-58	- 61	- 57	- 57	- 54
12	- 94	- 79	-168	-62	- 60	- 60	- 60	- 55
13	- 86	- 79	-185	-68	- 61	- 60	- 60	- 59
14	- 84	- 75	-198	-63	- 61	- 64	- 63	- 61
15	- 87	- 74	-225	-59	- 57	- 68	- 67	- 63
15.5	- 86	- 63	-252	-58	- 62	- 71	- 67	- 67
16	- 87	- 66	-233	-55	- 73	- 73	- 74	- 71
16.5	- 86	- 62	-235	-52	- 76	- 79	- 72	- 69
17	- 86	- 59	-235	-52	- 82	- 81	- 71	- 67
17.5	- 91	- 57	-281	-47	- 83	- 86	- 85	- 70
18	- 84	- 58	-301	-50	- 83	- 86	- 85	- 77
18.5	- 83	- 56	-330	-47	- 85	- 89	- 89	- 87
19	- 85	- 49		-44	- 89	- 89	- 89	- 87
19.5	- 82	- 33		-40	- 91	- 89	- 96	- 96
20	- 85	- 17		-33	- 96	-100	-101	- 96
21	- 75	+ 17		-28	-109	-108	-103	-100
22	+ 2	+ 52		-30	-111	-113	-113	-113
23	+ 68	+ 97		-14	-122	-123	-122	-113

i indicates before transfer

ii indicates after transfer

*NOTE: x 10^{-4} inches (+ tension, - compression)

TABLE B.3.3

DEFLECTIONS

LOAD (kips)	SOUTH * (in)	℄ (in)	NORTH * (in)
0	0	0	0
2	.05	.05	.05
4	.08	.08	.05
6	.11	.12	.10
8	.15	.16	.12
10	.19	.20	.17
11	.21	.24	.19
12	.24	.26	.21
13	.26	.29	.23
14	.30	.33	.27
14.5	.32	.35	.29
15	.34	.38	.30
15.5	.39	.44	.34
16	.45	.52	.41
16.5	.50	.57	.45
17	.55	.64	.51
17.5	.60	.69	.56
18	.64	.75	.60
18.5	.70	.82	.66
19	.75	.90	.77
19.5	.82	.98	.78
20	.87	1.05	.82
20.5	.95	1.15	.90
21	1.02	1.22	.97
21.5	1.09	1.30	1.04
22	1.15	1.37	1.10
22.5	1.28	1.54	1.21
23	1.42	1.70	1.34

* indicates 1/3 points

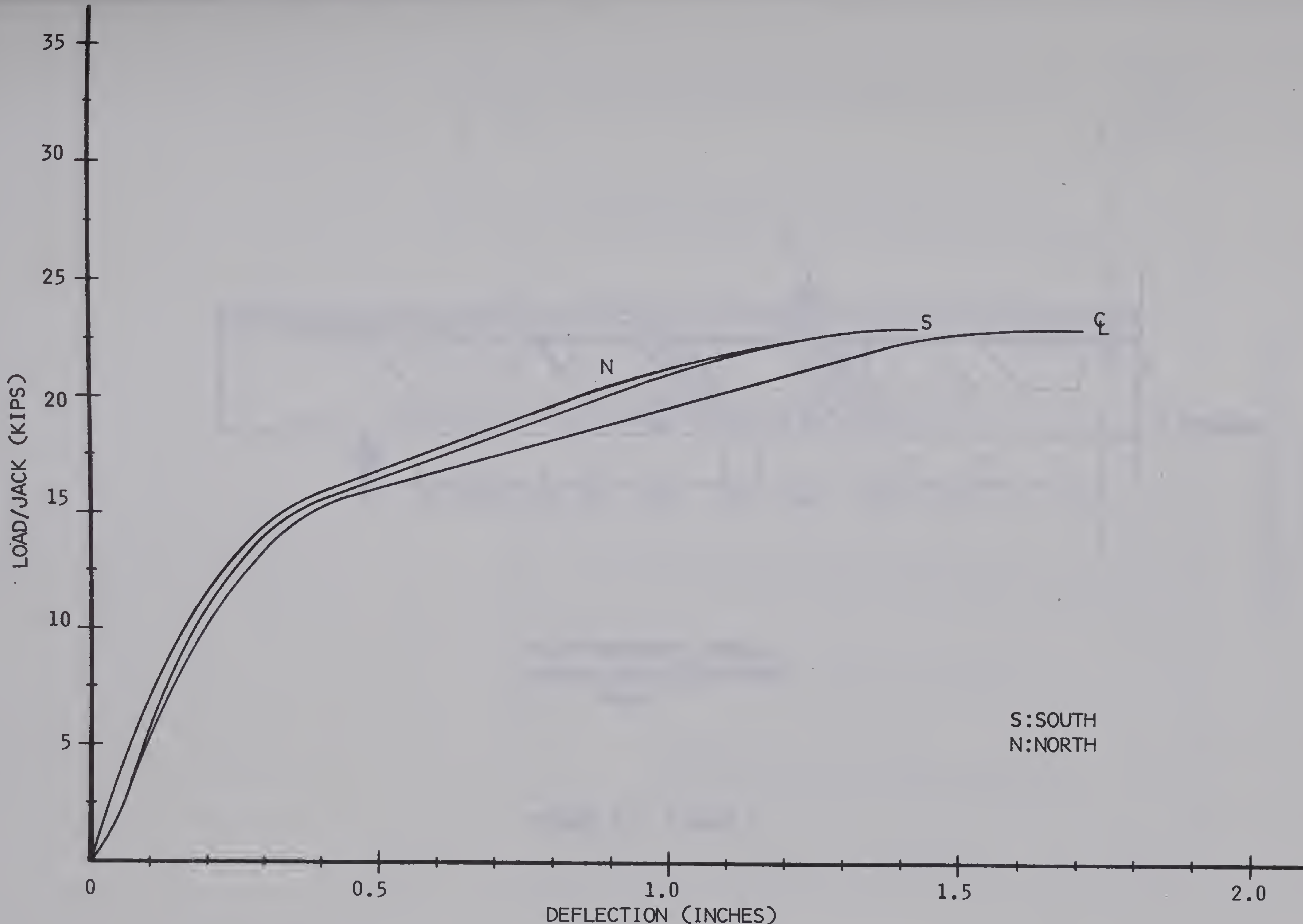
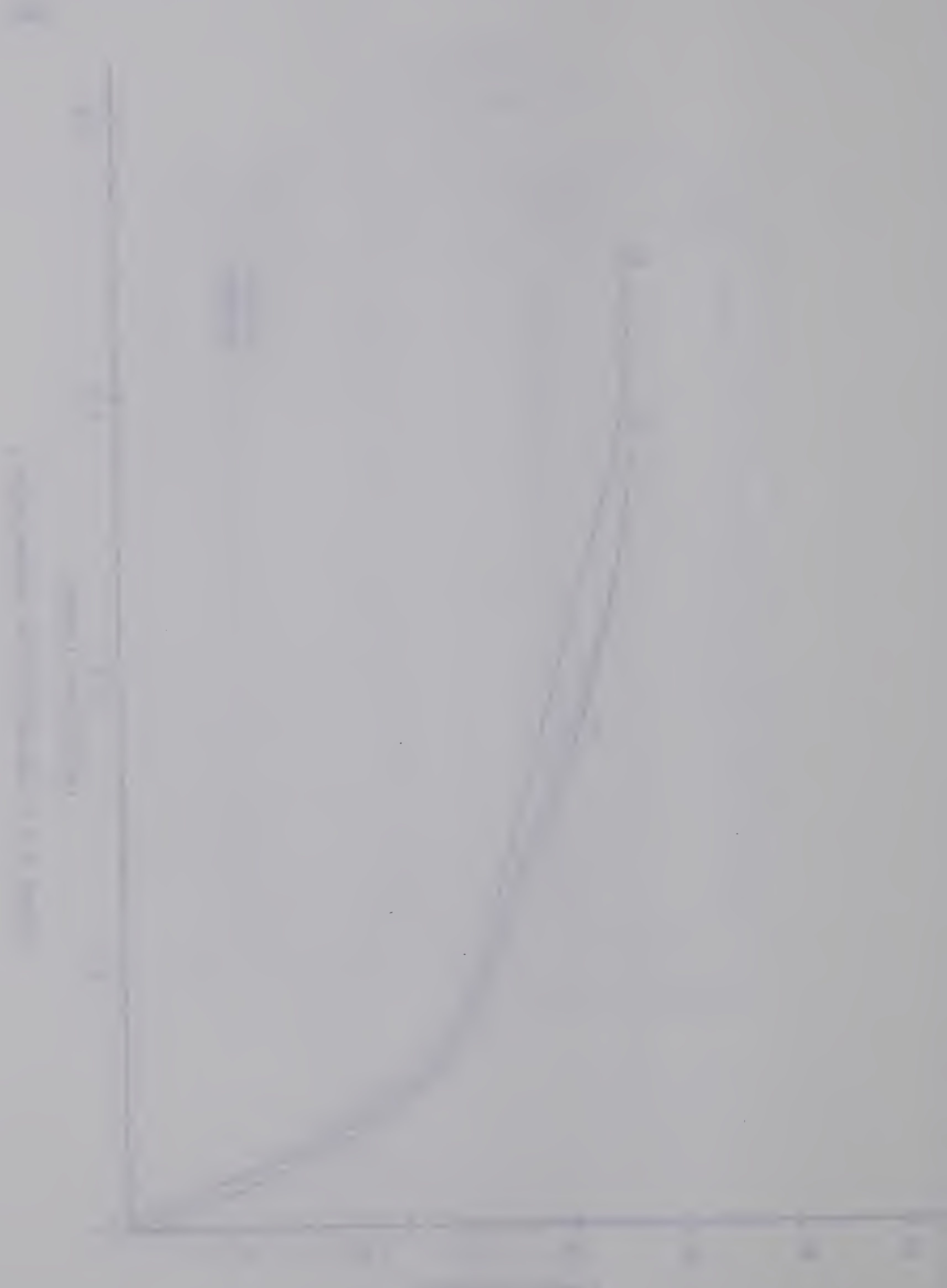
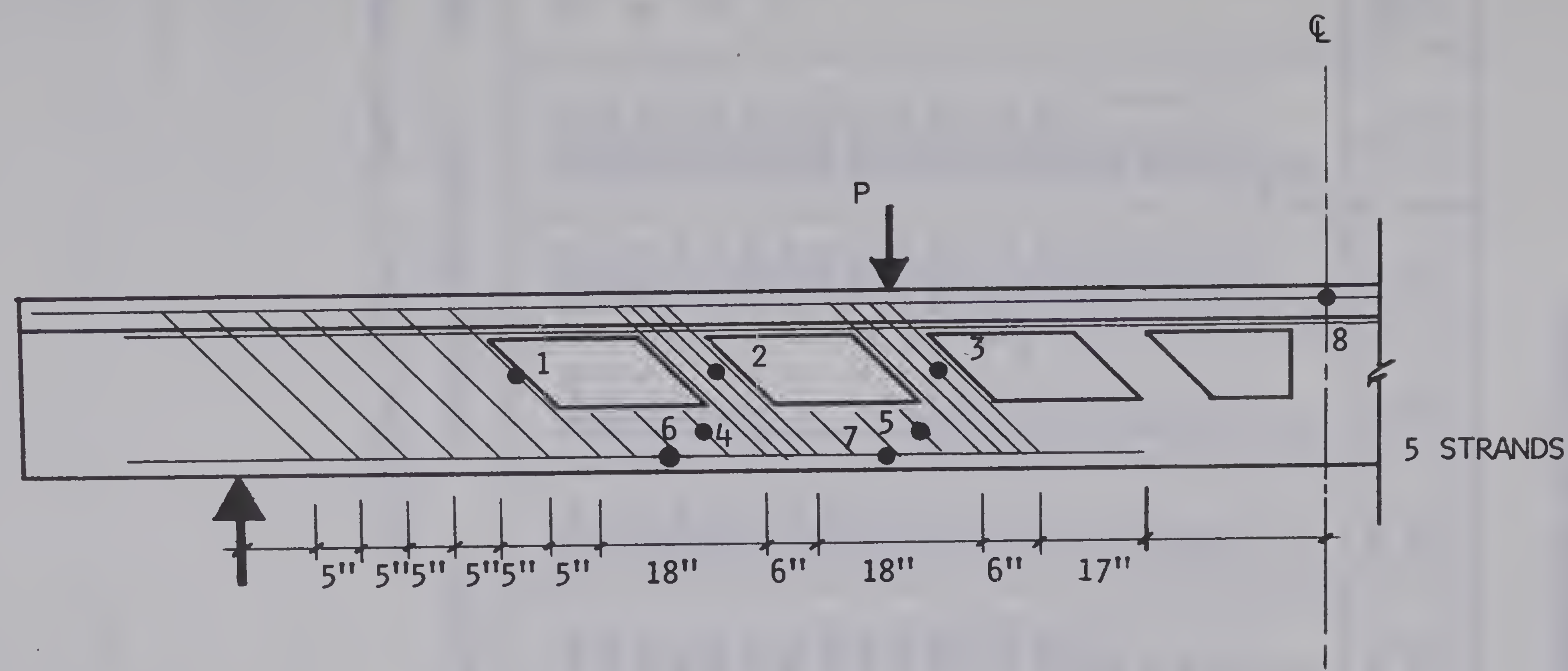


FIGURE B.3.2 LOAD-DEFLECTION DIAGRAM,BEAM 3





REINFORCEMENT DETAIL
STRAIN GAGE LOCATIONS
BEAM 4

FIGURE B.4.1 BEAM 4

TABLE B.4.1

STRAIN GAGE MEASUREMENTS

LOAD (kips)	(1) **	(2) **	(3) **	(4) **	(5) **	(6) **	(7) **	(8) **
0	0	0	0	0	0	0	0	0
2	+ 37*	+ 50	+ 6	+ 5	+ 9	+ 40	+ 80	- 25
4	+ 112	+159	+ 20	+ 19	+ 20	+ 95	+ 185	- 61
6	+ 220	+276	+ 35	+ 30	+ 36	+ 145	+ 300	- 98
8	+ 370	+361	+ 49	+ 40	+ 55	+ 190	+ 400	-130
10	+ 700	+460	+ 60	+ 65	+ 90	+ 240	+ 540	-170
12	+ 860	+545	+ 51	+ 90	+205	+ 310	+ 880	-205
14	+1065	+580	+ 39	+124	+497	+ 447	+ 1660	-222
15	+1150	+595	+ 38	+145	+565	+ 540	+ 1950	-228
16	+1250	+620	+ 38	+187	+655	+ 680	+ 2320	-231
17	+1320	+640	+ 39	+259	+690	+ 870	+ 2580	-231
18	+1400	+670	+ 17	+325	+740	+1100	+ 2860	-236
19	+1495	+680	+ 7	+435	+800	+1420	+ 3800	-220
20	+1560	+695	0	+481	+900	+1600	+11800	-200
20.5	+1610	+695	+ 8	+510	+930	+1700	+14300	-175
21	+1680	+695	+ 20	+520	+925	+1800	+15000	-140
21.5	+1710	+700	+ 25	+535	+930	+1850	+16000	-110
22	+1780	+700	+ 75	+550	+830	+1950	+27000	- 50
22.5	+1850	+715	+ 85	+555	+780	+2040	-	+ 60
23	+1850	+800	+149	+510	+575	+2000	-	+240
23.5	+1870	+810	+151	+500	+540	+2050	-	+415

* NOTE: + indicates tension; - indicates compression

** Measurements in micro inches/inch

TABLE B.4.2

DEMEC POINT MEASUREMENTS

LOAD (kips)	(1)	(2)	(3)	(5)	(6)	(7)	(8)	(9)
i	0	0	0	0	0	0	0	0
ii	- 74*	- 62	- 27	-18	+ 5	+ 6	+ 5	+ 4
0	-150	-128	-129	-47	- 8	- 6	- 4	- 14
2	-146	-125	-126	-49	- 5	- 10	- 7	- 22
4	-134	-116	-120	-50	- 14	- 12	- 24	- 27
6	-125	-109	-113	-54	- 27	- 31	- 32	- 24
8	-119	-103	-109	-59	- 34	- 29	- 34	- 38
10	-103	- 93	- 98	-62	- 30	- 38	- 38	- 44
12	- 86	- 83	- 97	-62	- 48	- 49	- 53	- 55
13	- 34	- 59	- 96	-62	- 52	- 60	- 62	- 63
14	+ 1	- 32	- 80	-54	- 57	- 71	- 66	- 66
15	+ 28	+ 24	- 74	-51	- 71	- 73	- 75	- 78
15.5	+ 49	+ 55	- 67	-46	- 73	- 76	- 79	- 80
16	+ 73	+ 86	- 38	-41	- 80	- 83	- 84	- 86
16.5	+ 96	+105	- 15	-38	- 84	- 93	- 85	- 91
17	+117	+127	+ 7	-34	- 84	- 91	- 93	- 93
17.5	+137	+132	+ 32	-32	- 91	- 95	- 96	- 98
18	+162	+174	+ 53	-28	- 96	-106	-101	-104
18.5	+194	+209	+ 86	-20	-101	-107	-112	-112
19	+242	+242	+121	-11	-106	-114	-114	-113
19.5	+267	+278	+156	- 8	-106	-115	-120	-118
20	+308	+310		- 3	-115	-127	-125	-127
20.5	+383	+368		+ 2	-122	-127	-129	-129
20.75	+437	+410		+ 8	-126	-135	-137	-139
21.0	+490	+452		+ 7	-130	-141	-143	-142
21.5								
23.5	failure							

i indicates before transfer

ii indicates after transfer

*NOTE: x 10^{-4} inches (+ tension, - compression)

TABLE B.4.3

DEFLECTIONS

LOAD (kips)	SOUTH * (in)	℄ (in)	NORTH * (in)
0	0	0	0
2	.01	.10	.10
4	.06	.15	.16
6	.12	.22	.22
8	.17	.28	.27
10	.25	.36	.34
12	.37	.52	.47
14	.59	.80	.69
16	.84	1.10	.91
17	.95	1.24	1.02
17.5	1.01	1.32	1.09
18	1.06	1.40	1.14
18.5	1.14	1.51	1.23
19	1.26	1.64	1.32
19.5	1.34	1.75	1.42
20	1.44	1.87	1.50
20.5	1.55	2.00	1.64
21	1.73	2.26	1.82
21.5	1.90	2.47	1.98
22	2.16	2.82	2.24
22.5	2.63	3.45	2.71
23	3.31	4.31	3.35
23.5	3.96	5.05	3.98

* indicates 1/3 points

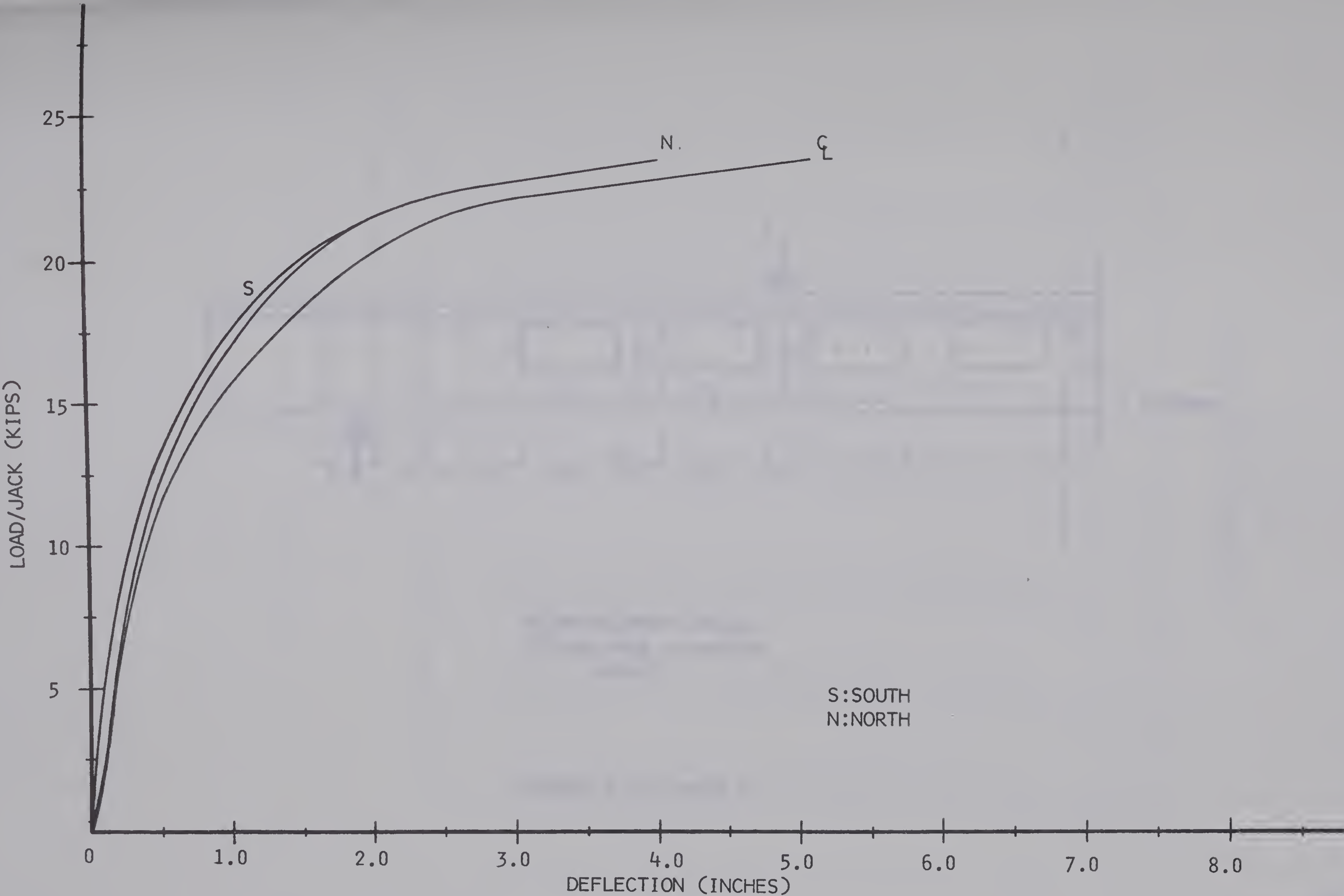
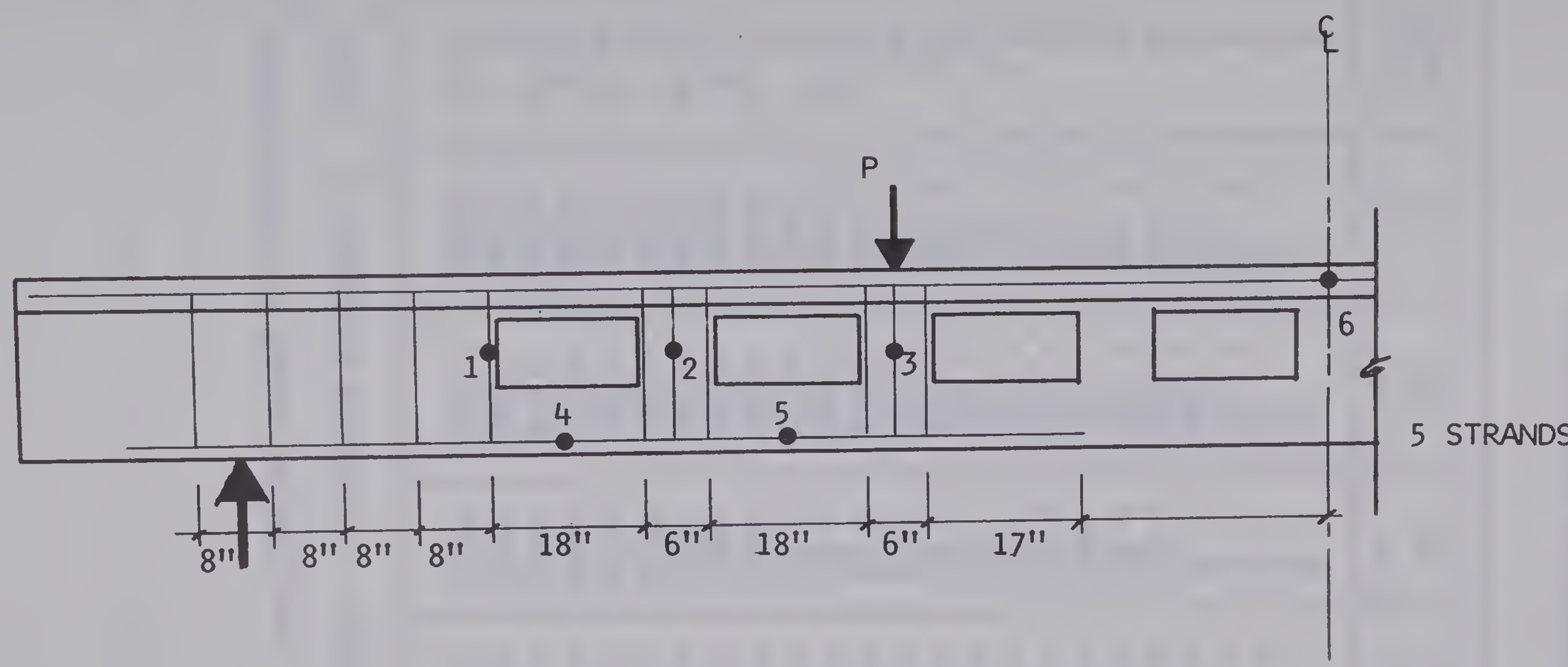


FIGURE B.4.2 LOAD-DEFLECTION DIAGRAM, BEAM 4



REINFORCEMENT DETAIL
STRAIN GAGE LOCATIONS
BEAM 5

FIGURE B.5.1 BEAM 5

TABLE B.5.1

STRAIN GAGE MEASUREMENTS

LOAD (kips)	(1) **	(2) **	(3) **	(4) **	(5) **	(6) **
0	0	0	0	0	0	0
2	+ 14*	+ 5	- 2	+ 28	+ 55	- 30
4	+ 84	+ 42	- 6	+ 62	+ 128	- 70
6	+ 250	+ 164	+ 5	+ 112	+ 224	-110
8	+ 414	+ 355	+ 15	+ 160	+ 310	-144
10	+ 646	+ 510	+ 38	+ 230	+ 444	-190
11	+ 760	+ 570	+ 50	+ 280	+ 570	-212
12	+ 860	+ 856	+ 60	+ 312	+1002	-232
12.5	+ 878	+ 890	+ 62	+ 330	+1104	-242
13	+ 898	+ 922	+ 62	+ 354	+1236	-250
13.5	+ 928	+ 975	+ 65	+ 390	+1424	-256
14	+ 956	+1022	+ 70	+ 424	+1600	-262
14.5	+ 986	+1070	+ 78	+ 456	+1728	-268
14.75	+1002	+1090	+ 86	+ 476	+1790	-270
15	+1020	+1112	+ 96	+ 498	+1844	-275
15.25	+1042	+1135	+105	+ 528	+1925	-276
15.5	+1064	+1178	+122	+ 558	+2014	-280
15.75	+1080	+1208	+128	+ 596	+2100	-284
16	+1104	+1238	+134	+ 660	+2185	-286
16.25	+1120	+1256	+136	+ 710	+2260	-286
16.5	+1185	+1270	+144	+ 782	+2330	-288
16.75	+1206	+1276	+146	+ 946	+2400	-290
17	+1242	+1290	+550	+1048	+2460	-290
17.25	+1266	+1300	+570	+1124	+2510	-290

* NOTE: + indicates tension; - indicates compression

** Measurements in micro inches/inch

TABLE B.5.2

DEMEC POINT MEASUREMENTS

LOAD (kips)	(1)	(2)	(3)	(5)	(6)	(7)	(8)	(9)
i	0	0	0	0	0	0	0	0
ii	- 69*	- 63	- 54	-14	+ 2	+ 4	+ 4	0
0	-151	-143	-133	-59	- 28	- 13	- 29	- 27
2	-145	-136	-132	-70	- 30	- 31	- 34	- 34
4	-137	-130	-128	-69	- 34	- 30	- 40	- 42
6	-128	-122	-122	-70	- 40	- 41	- 45	- 49
8	-120	-115	-117	-73	- 41	- 48	- 51	- 57
10	-105	-104	-108	-72	- 52	- 54	- 57	- 60
11	- 99	- 99	-106	-76	- 54	- 58	- 62	- 62
12	- 90	- 93	-101	-73	- 60	- 63	- 66	- 73
12.5	- 73	- 83	- 96	-79	- 65	- 66	- 69	- 76
13	- 31	- 51	- 86	-72	- 61	- 70	- 74	- 78
13.5	+ 11	- 13	- 40	-78	- 76	- 78	- 80	- 88
14	+ 35	+ 21	- 2	-64	- 82	- 83	- 89	- 87
14.5	+ 18	+ 24	+ 33	-65	- 88	- 91	- 88	- 94
14.75	+ 14	+ 27	+ 37	-64	- 84	- 91	- 90	- 95
15	+ 11	+ 29	+ 44	-64	- 92	- 95	- 99	-100
15.25	+ 12	+ 36	+ 56	-62	- 90	- 91	- 99	- 95
15.5	+ 16	+ 41	+ 64	-57	- 93	- 97	- 89	-104
15.75	+ 12	+ 39	+ 85	-74	- 92	-103	-103	-105
16	+ 21	+ 48	+ 73	-57	-103	-104	-109	-112
16.25	+ 26	+ 56	+ 80	-57	- 99	-101	-106	-109
16.5	+ 32	+ 62	+ 90	-56	- 94	- 97	-109	-112
16.75	+ 35	+ 65	+ 94	-54	-103	-106	-114	-116
17.0								
17.25	failure							

i indicates before transfer

ii indicates after transfer

*NOTE: x 10^{-4} inches, (+ tension, - compression)

TABLE B.5.3

DEFLECTIONS

LOAD (kips)	SOUTH * (in)	℄ (in)	NORTH * (in)
0	0	0	0
2	.03	.04	.03
4	.09	.10	.08
6	.14	.17	.13
8	.20	.23	.19
10	.28	.32	.25
11	.34	.38	.32
12	.41	.46	.39
12.5	.45	.51	.43
13	.50	.59	.50
13.5	.60	.70	.57
14	.69	.84	.68
14.5	.79	.93	.74
15	.85	1.00	.83
15.25	.88	1.05	.85
15.5	.94	1.12	.92
15.75	.99	1.18	.96
16	1.04	1.24	1.01
16.25	1.13	1.33	1.06
16.5	1.19	1.38	1.10
16.75	1.23	1.44	1.15
17	1.28	1.50	1.20
17.25	1.34	1.56	1.24

* indicates 1/3 points

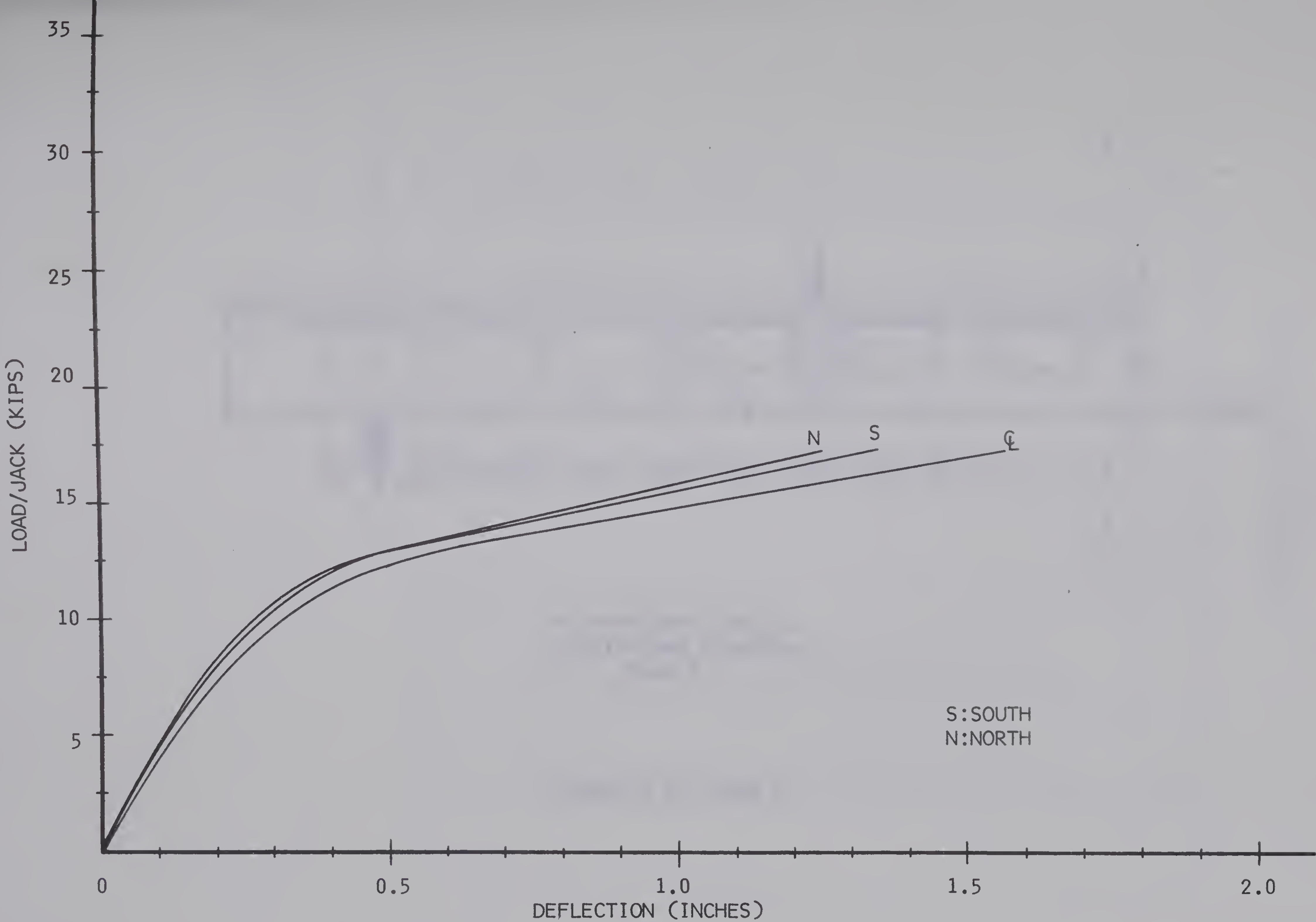
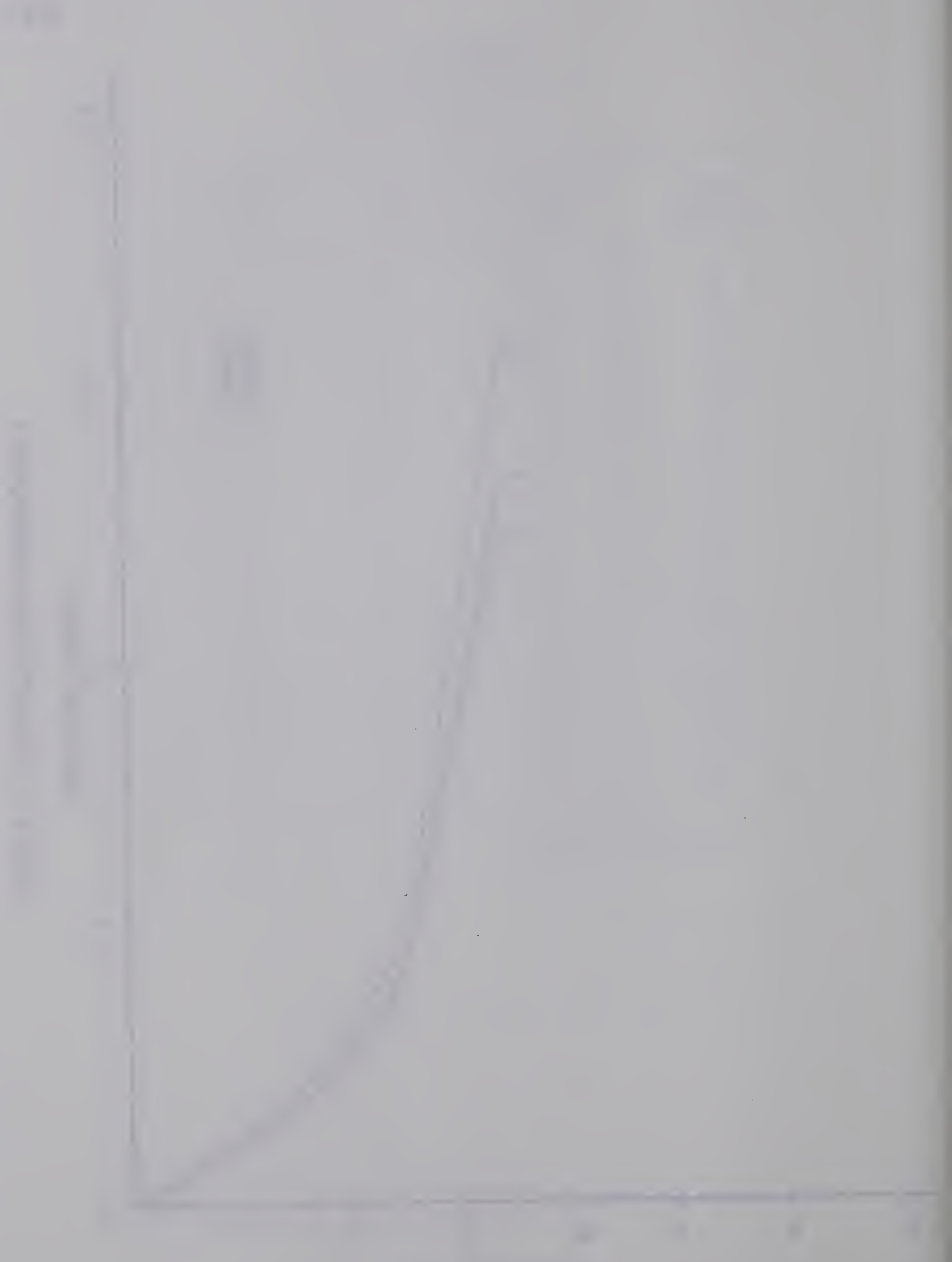
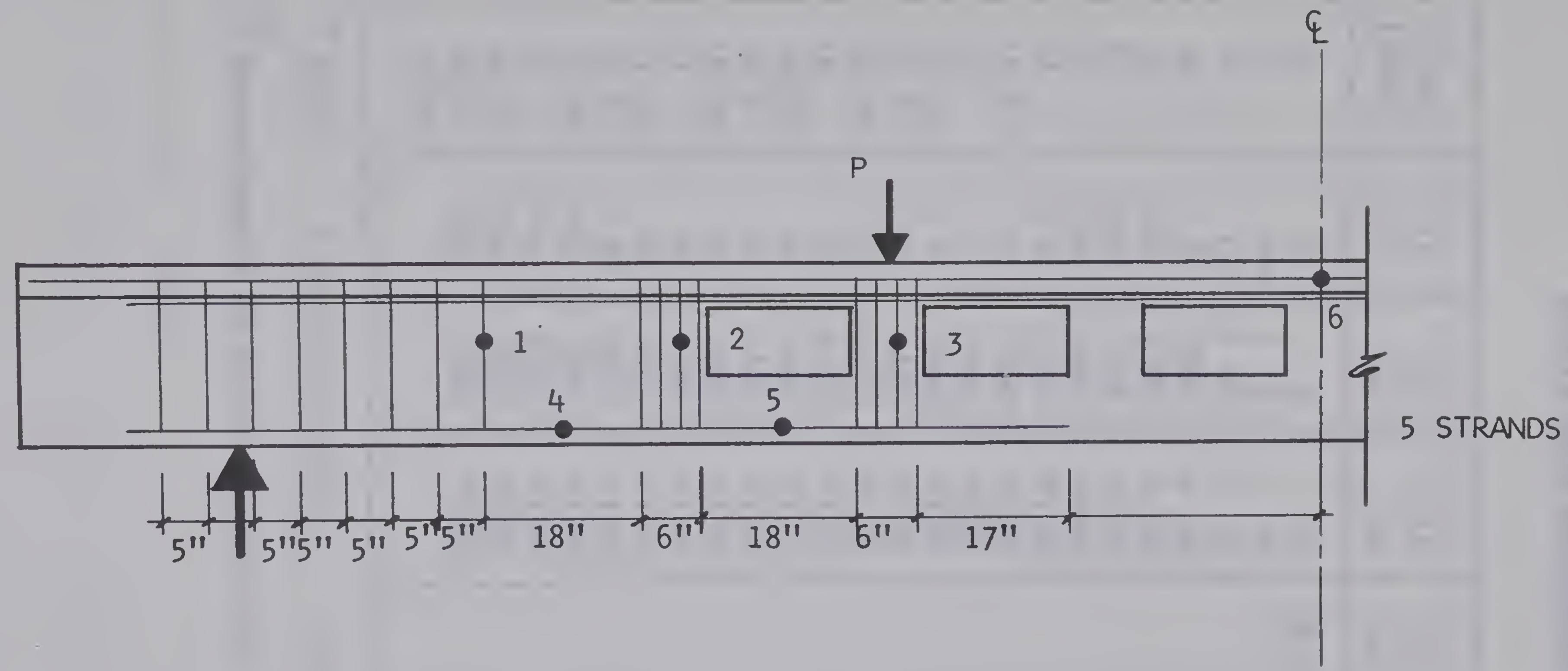


FIGURE B.5.2 LOAD-DEFLECTION DIAGRAM,BEAM 5





REINFORCEMENT DETAIL
STRAIN GAGE LOCATIONS
BEAM 6

FIGURE B.6.1 BEAM 6

TABLE B.6.1

STRAIN GAGE MEASUREMENTS

LOAD (kips)	(1) **	(2) **	(3) **	(4) **	(5) **	(6) **
0	0	0	0	N.A.	0	0
2	- 4*	+ 18	- 4		+ 56	- 34
4	0	+ 88	+ 5		+ 132	- 76
6	+ 2	+202	+ 26		+ 214	-120
8	+12	+320	+ 46		+ 295	-156
10	+24	+356	+120		+ 432	-202
12	+30	+370	+156		+ 854	-244
14	+ 8	+436	+122		+1615	-278
14.5	+ 2	+458	+130		+1720	-286
15	0	+460	+126		+1848	-292
15.25	+ 4	+468	+126		+1936	-300
15.5	+ 4	+468	+126		+2026	-304
15.75	+ 2	+470	+123		+2130	-308
16	0	+476	+122		+2228	-315
16.25	0	+482	+120		+2312	-316
16.5	0	+490	+118		+2374	-320
16.75	0	+494	+112		+2458	-322
17	0	+500	+112		+2534	-324
17.25	0	+510	+145		+2604	-328
17.5	+ 8	+518	+144		+2680	-332
17.75	+12	+524	+146		+2756	-330
18	+14	+530	+146		+2815	-334
18.25	+16	+535	+145		+2898	-335
18.5	+20	+546	+145		+2990	-340
18.75						

* NOTE: + indicates tension; - indicates compression

** Measurements in micro inches/inch

TABLE B.6.2

DEMEC POINT MEASUREMENTS

LOAD (kips)	(1)	(2)	(3)	(5)	(6)	(7)	(8)	(9)
i	0	0	0	0	0	0	0	0
ii	- 83*	- 67	- 50	-19	+ 3	+ 4	+ 5	+ 4
0	-162	-139	-126	-53	- 43	- 27	- 10	- 12
2	-154	-136	-124	-52	- 46	- 20	- 18	- 6
4	-147	-134	-118	-53	- 46	- 37	- 28	- 15
6	-137	-124	-119	-54	- 50	- 37	- 38	- 27
8	-129	-118	-110	-59	- 49	- 44	- 40	- 42
10	-115	-107	-107	-66	- 58	- 50	- 49	- 51
12	- 86	- 94	-105	-67	- 66	- 58	- 56	- 59
14	- 19	- 35	- 40	-57	- 83	- 75	- 74	- 79
14.5	+ 4	- 7	- 12	-59	- 84	- 77	- 82	- 82
15	+ 23	+ 7	+ 3	-61	- 87	- 81	- 83	- 86
15.25	+ 36	+ 20	+ 15	-54	- 93	- 87	- 79	- 84
15.5	+ 46	+ 30	+ 28	-55	- 92	- 89	- 88	- 89
15.75	+ 60	+ 47	+ 44	-53	- 90	- 88	- 91	- 93
16	+ 72	+ 54	+ 50	-55	- 98	- 90	- 93	- 96
16.25	+ 87	+ 67	+ 62	-50	- 98	- 91	- 94	- 99
16.5	+ 93	+ 73	+ 70	-49	- 94	- 95	- 99	-103
16.75	+103	+ 82	+ 78	-49	-100	- 89	-101	-105
17	+111	+ 84	+ 82	-46	-101	- 93	- 97	-111
17.25	+121	+ 98	+ 86	-43	-103	- 93	-105	-111
17.5	+136	+101	+ 88	-43	-110	-103	-107	-112
17.75	+144	+113	+ 97	-43	-113	-107	-110	-113
18	+157	+123	+107	-36	-106	-107	-107	-112
18.25	+164	+137	+109	-33	-106	-112	-117	-118
18.5	+194	+137	+108	-30	-125	-106	-117	-126
18.75	failure							

i indicates before transfer

ii indicates after transfer

*NOTE: x 10^{-4} inches, (+ tension, - compression)

TABLE B.6.3

DEFLECTIONS

LOAD (kips)	SOUTH * (in)	℄ (in)	NORTH * (in)
0	0	0	0
2	.05	.05	.04
4	.10	.12	.09
6	.18	.19	.14
8	.22	.25	.20
10	.29	.33	.26
12	.40	.46	.36
14	.68	.79	.62
15	.81	.95	.75
15.5	.88	1.05	.83
15.75	.92	1.11	.87
16	.97	1.16	.91
16.25	1.00	1.21	.96
16.5	1.04	1.26	.97
16.75	1.08	1.31	1.02
17	1.11	1.34	1.06
17.25	1.15	1.39	1.10
17.5	1.18	1.44	1.12
17.75	1.22	1.49	1.17
18	1.25	1.54	1.21
18.25	1.30	1.59	1.24
18.5	1.35	1.66	1.30
18.75	1.45	1.74	1.42

* indicates 1/3 points

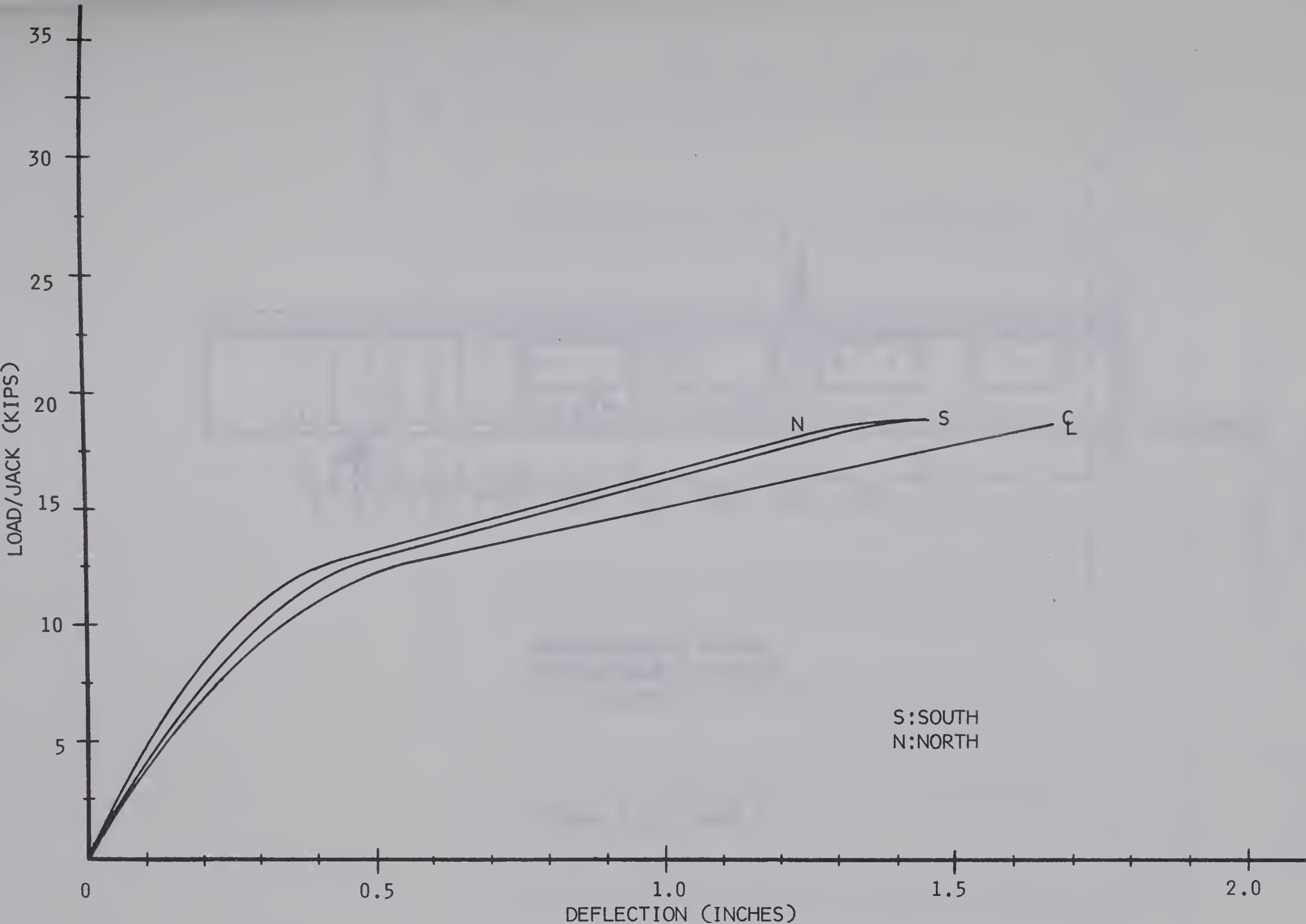
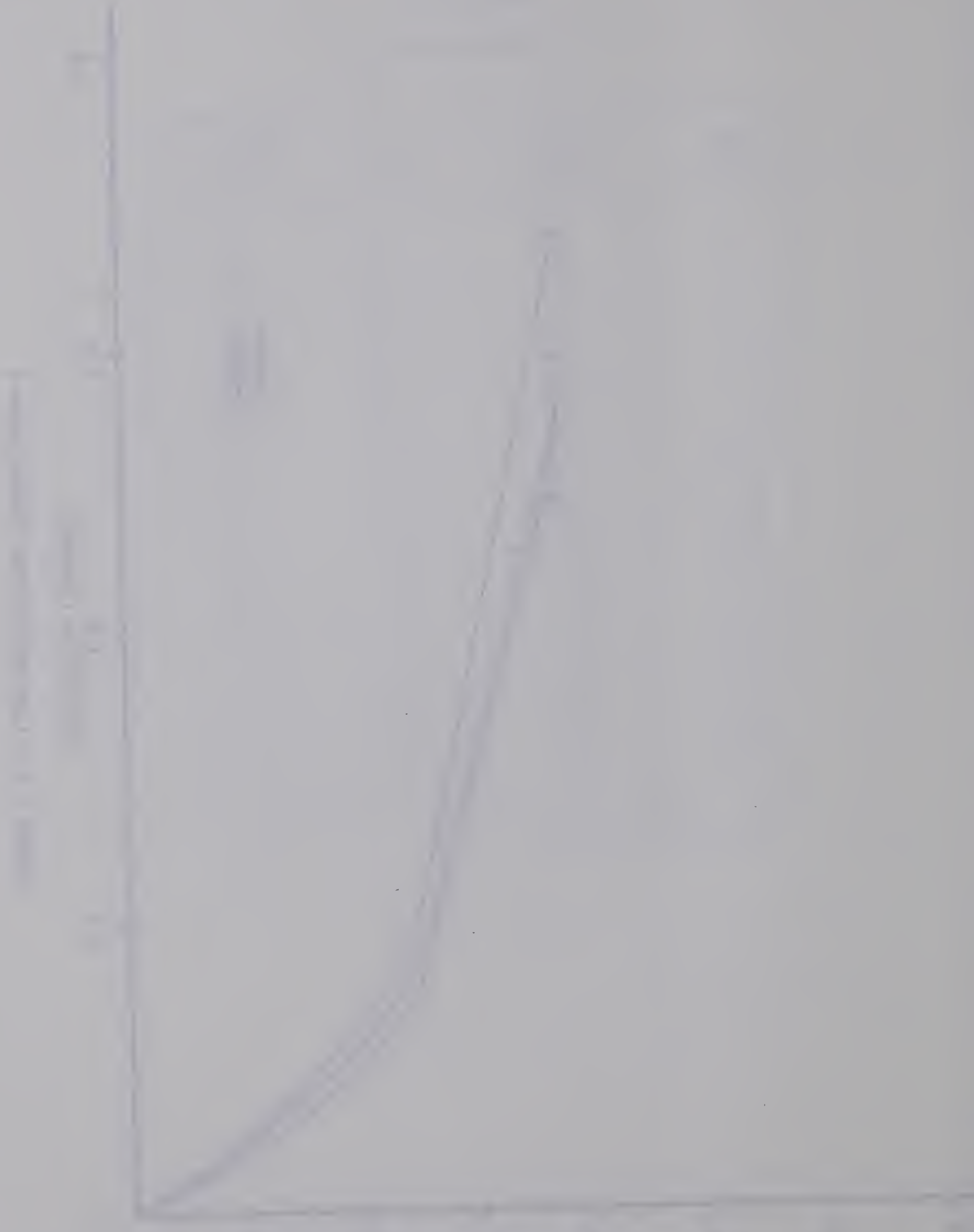
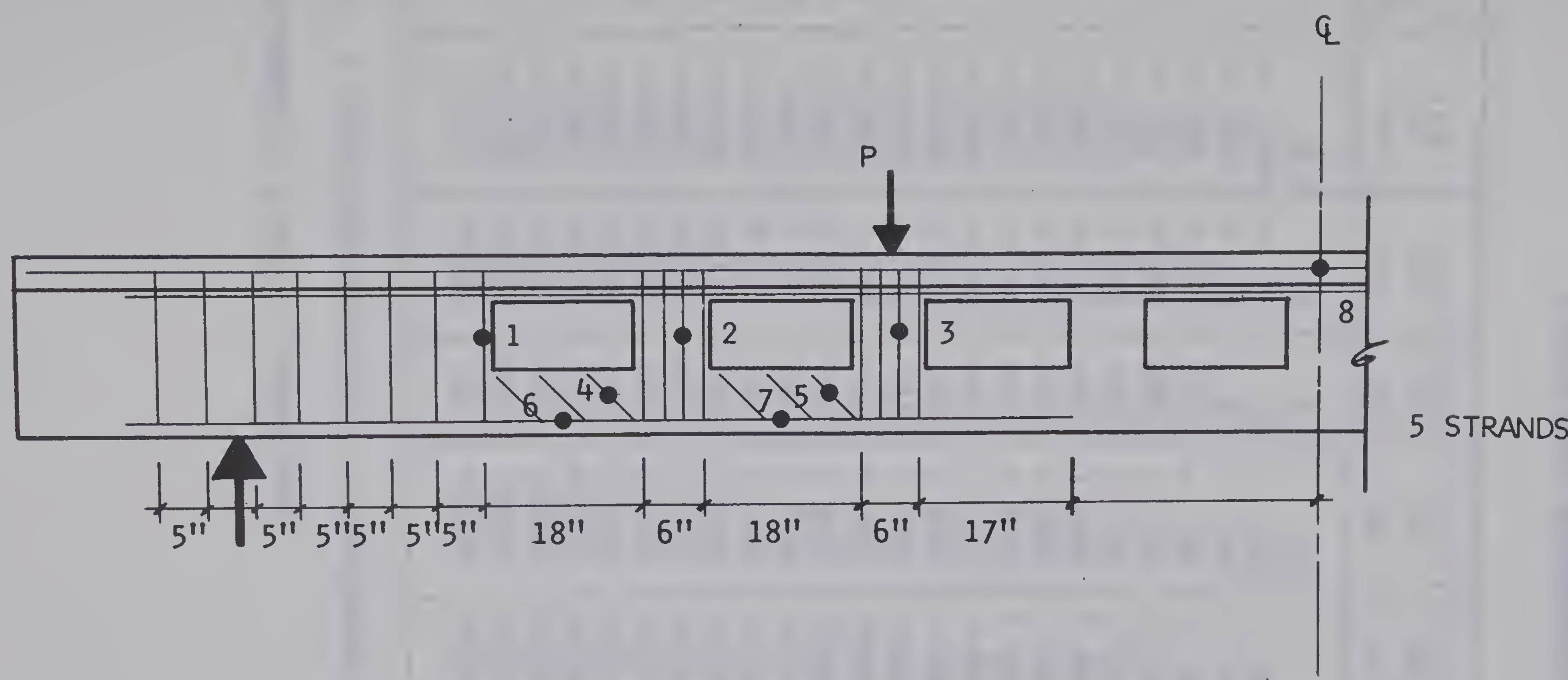


FIGURE B.6.2 LOAD-DEFLECTION DIAGRAM,BEAM 6





REINFORCEMENT DETAIL
STRAIN GAGE LOCATIONS
BEAM 7

FIGURE B.7.1 BEAM 7

TABLE B.7.1

STRAIN GAGE MEASUREMENTS

LOAD (kips)	(1) **	(2) **	(3) **	(4) **	(5) **	(6) **	(7) **	(8) **
0	0	0	0	0	0	0	0	0
2	+ 24*	+ 17	- 3	+ 20	+ 24	+ 36	+ 58	- 47
4	+ 111	+ 126	- 3	+ 54	+ 54	+ 78	+ 152	- 110
6	+ 334	+ 410	+14	+ 84	+ 95	+ 132	+ 233	- 166
8	+ 527	+ 580	+24	+ 116	+ 140	+ 190	+ 342	- 213
10	+ 757	+ 690	+40	+ 158	+ 263	+ 285	+ 573	- 267
12	+1057	+ 716	+50	+ 244	+ 580	+ 450	+ 920	- 321
13	+1077	+ 737	+44	+ 308	+ 705	+ 599	+1112	- 344
14	+1101	+ 744	+41	+ 542	+ 853	+ 868	+1384	- 364
14.5	+1148	+ 758	+40	+ 595	+ 906	+ 934	+1476	- 370
15	+1184	+ 765	+40	+ 646	+ 960	+1014	+1579	- 381
15.5	+1231	+ 770	+41	+ 712	+1028	+1122	+1720	- 382
15.75	+1307	+ 794	+42	+ 764	+1060	+1202	+1787	- 395
16	+1367	+ 812	+45	+ 802	+1091	+1262	+1862	- 398
16.25	+1420	+ 832	+48	+ 836	+1116	+1312	+1929	- 405
16.5	+1448	+ 871	+49	+ 988	+1146	+1540	+2056	- 407
16.75	+1916	+1170	+50	+1092	+1172	+1632	+2118	- 406
17	+2002	+1238	+23	+1128	+1192	+1688	+2174	- 417
17.25	+2022	+1252	+19	+1154	+1210	+1728	+2221	- 416
17.5	+2055	+1283	+18	+1186	+1233	+1780	+2275	- 416
17.75	+2080	+1313	+19	+1220	+1256	+1838	+2319	- 419
18	+2092	+1351	+18	+1254	+1260	+1896	+2356	- 421
18.25	+2105	+1414	+19	+1297	+1272	+1978	+2412	- 420
18.5	+2116	+1500	+32	+1346	+1256	-1144	- 33	-1212

* NOTE: + indicates tension; - indicates compression

** Measurements in micro inches/inch

TABLE B.7.2

DEMEC POINT MEASUREMENTS

LOAD (kips)	(1)	(2)	(3)	(5)	(6)	(7)	(8)	(9)
i	0	0	0	0	0	0	0	0
ii	- 80*	- 65	- 49	-15	+ 1	+ 5	+ 5	+ 4
0	-156	-133	-116	-52	-28	-23	- 13	- 30
2	-184	-125	-110	-51	-30	-26	- 18	- 32
4	-138	-117	-108	-61	-36	-24	- 49	- 36
6	-129	-113	-101	-59	-39	-35	- 37	- 45
8	-119	-108	- 99	-65	-42	-39	- 43	- 47
10	-109	-104	- 94	-68	-48	-45	- 52	- 57
12	- 79	- 87	- 91	-68	-53	-51	- 59	- 67
13	- 65	- 76	- 86	-63	-67	-65	- 61	- 73
14	+ 4	- 7	- 15	-54	-74	-68	- 71	- 85
14.5	+ 26	+ 11	+ 5	-49	-81	-71	- 79	- 89
15	+ 46	+ 32	+ 23	-47	-80	-77	- 84	- 93
15.5	+ 76	+ 58	+ 48	-42	-82	-84	- 86	- 99
15.75	+ 91	+ 71	+ 58	-45	-94	-91	- 86	- 99
16	+108	+ 81	+ 58	-36	-91	-91	- 96	-106
16.25	+125	+ 90	+ 63	-36	-92	-92	- 93	-106
16.5	+136	+ 95	+ 62	-38	-94	-91	- 93	-108
16.75	+150	+105	+ 69	-35	-96	-99	-101	-109
18.5	failure							

i indicates before transfer

ii indicates after transfer

*NOTE: x 10^{-4} inches, (+ tension, - compression)

TABLE B.7.3

DEFLECTIONS

LOAD (kips)	SOUTH * (in)	℄ (in)	NORTH * (in)
0	0	0	0
2	.04	.05	.04
4	.11	.14	.11
6	.18	.21	.17
8	.24	.28	.23
10	.33	.38	.32
12	.46	.54	.46
13	.55	.65	.55
14	.76	.91	.76
14.5	.82	.99	.82
15	.89	1.07	.89
15.5	.98	1.18	.98
15.75	1.03	1.25	1.03
16	1.08	1.31	1.08
16.25	1.12	1.36	1.12
16.75	1.21	1.49	1.24
17	1.26	1.55	1.29
17.25	1.30	1.60	1.33
17.5	1.34	1.66	1.38
17.75	1.39	1.71	1.43
18	1.43	1.77	1.48
18.25	1.49	1.85	1.54
18.5	1.62	2.06	1.67

* indicates 1/3 points

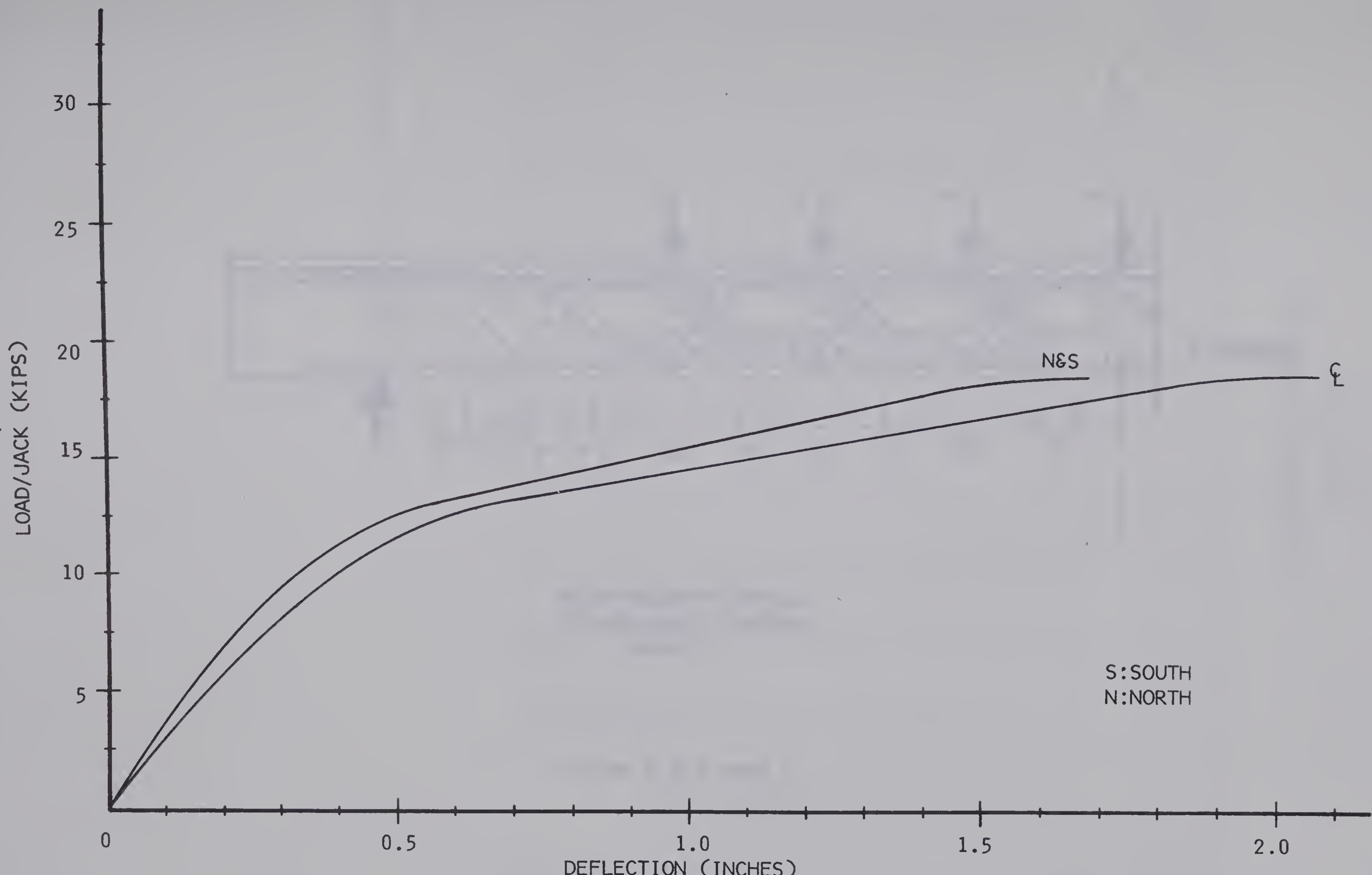
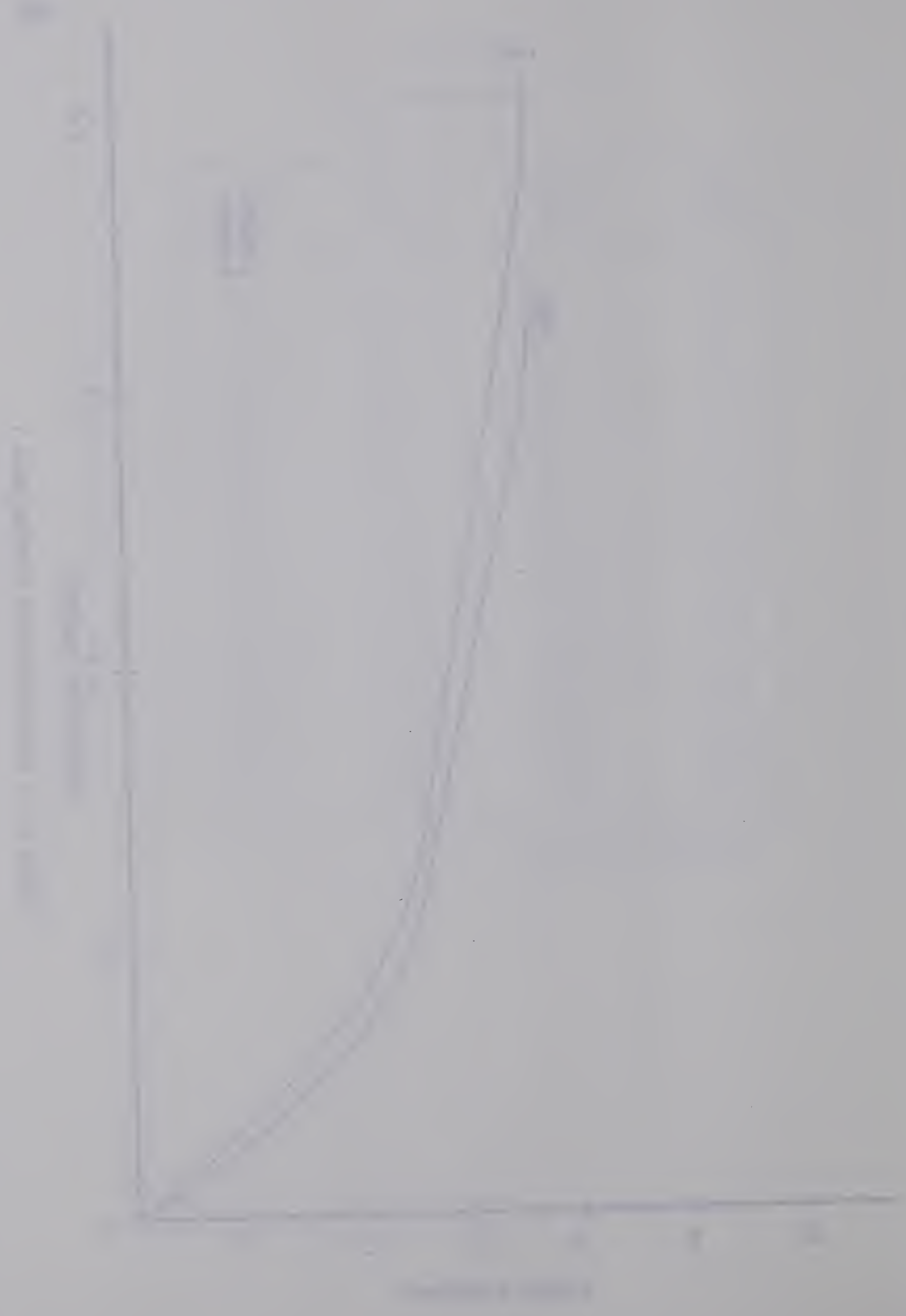
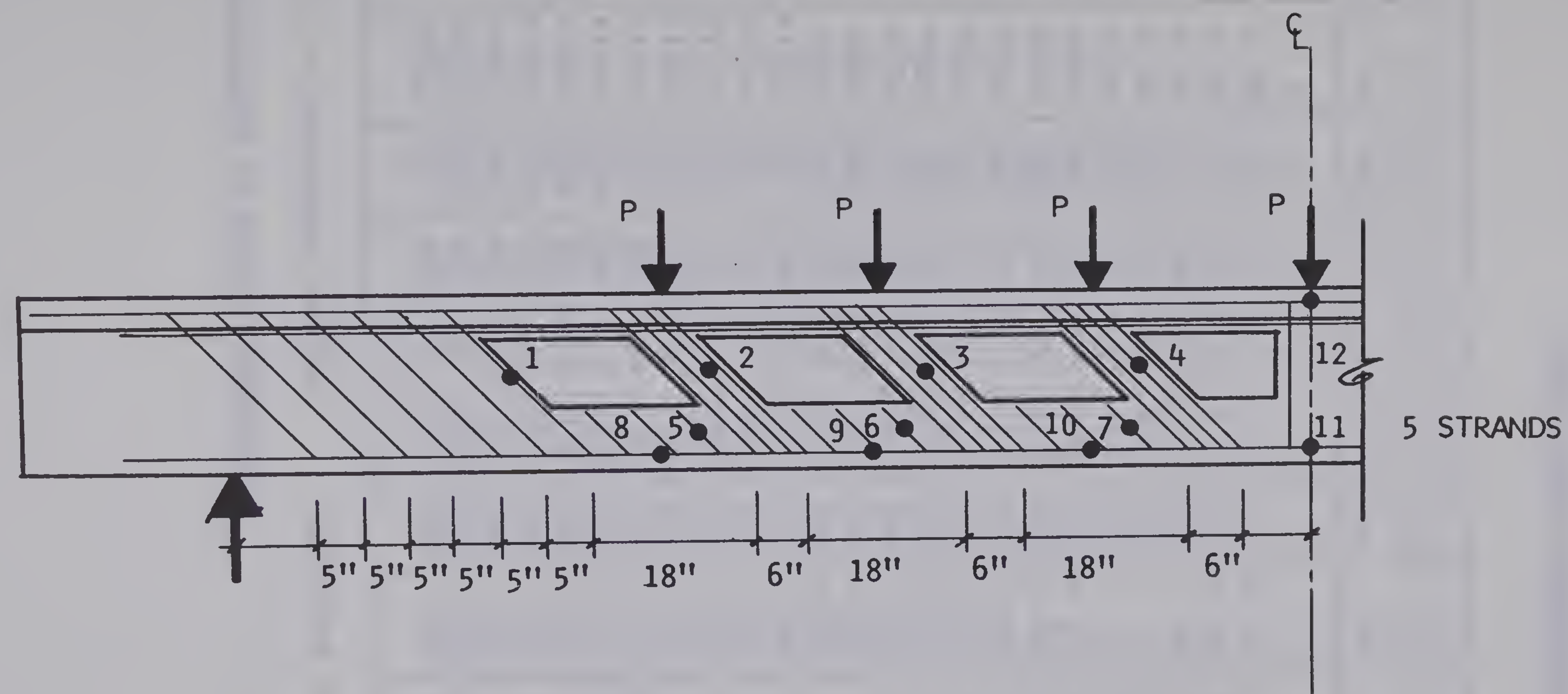


FIGURE B.7.2 LOAD-DEFLECTION DIAGRAM,BEAM 7





REINFORCEMENT DETAIL
STRAIN GAGE LOCATIONS
BEAM 8

FIGURE B.8.1 BEAM 8

TABLE B.8.1

STRAIN GAGE MEASUREMENTS

LOAD (kips)	(1) **	(2) **	(3) **	(4) **	(5) **	(6) **	(7) **	(8) **	(9) **	(10) **	(11) **	(12) **
0	0	0	0	0	0	0	0	0	0	0	0	0
.4	+ 15*	+15	+11	+ 4	+ 3	+ 6	+ 8	+ 39	+ 54	+ 55	+ 65	- 23
.8	+ 36	+38	+34	+11	+ 5	+11	+ 18	+ 82	+111	+114	+133	- 49
1.25	+ 58	+72	+64	+18	+ 6	+15	- 16	+121	+168	+172	+200	- 74
1.65	+ 94	150	105	+30	+10	+21	- 6	+166	+235	+241	+276	-101
2.0	+134	262	139	+40	+14	+29	- 17	+214	+302	+315	+359	-127
2.35	+169	334	170	+55	+16	+36	+ 67	+256	+376	+404	+456	-150
2.85	+197	390	194	+70	+19	+50	+ 99	+324	+484	+556	+639	-182
3.25	+216	435	213	+73	+24	+80	+156	+387	+613	+765	+930	-203
3.65	+247	490	212	+80	+32	166	+191	+463	+855	+1060	+1400	-225
4.0	+560	528	222	+98	+39	283	+357	+540	1100	+1288	+1740	-240
4.55	+750	573	240	165	+61	395	+502	+725	1480	+1680	+2280	-268
4.9	+866	600	259	203	+92	439	+550	+968	1780	+1970	+2700	-286
5.25	+972	627	280	235	131	486	+592	1164	2060	+2280	+3760	-304
5.65	+1032	652	296	269	141	520	+648	1395	2320	+2460	+5080	-323
5.95	+1094	687	307	351	160	560	+700	1560	2560	+2480	+5880	-326
6.3	+1174	720	318	418	170	616	+732	1760	2810	+2510	+7150	-318
6.7	+1280	756	340	496	178	665	+752	1970	2860	+2480	+10520	-300
7.0	+1362	783	366	558	182	700	+730	2120	2850	+2460	+14350	-256
7.25	+1416	809	384	600	188	726	+712	2260	2850	+2550		-132
7.375	+1445	820	393	618	190	740	+707	2330	2860	+2600		- 79
7.5	+1463	828	400	633	193	753	+708	2380	2860	+2590		- 15
7.75	+1500	843	416	662	198	800	+708	2510	2850	+2540		+149
8	+1530	860	429	677	203	820	+728	2620	2860	10000		+360
8.25	+1560	867	445	735	200	798	+718	2700	2890			+820

* NOTE: + indicates tension; - indicates compression

** Measurements in micro inches/inch

TABLE B.8.2

DEMEC POINT MEASUREMENTS

LOAD (kips)	(1)	(2)	(3)	(5)	(6)	(7)	(8)	(9)
i	0	0	0	0	0	0	0	0
ii	- 60*	- 61	- 67	-15	0	+ 3	+ 1	+ 4
0	- 99	-102	-110	-34	- 24	- 21	- 28	- 29
0.4	- 89	- 97	-106	-72	- 23	- 20	- 28	- 33
0.8	- 87	- 99	-104	-29	- 29	- 26	- 30	- 33
1.25	- 77	- 91	-102	-31	- 29	- 32	- 35	- 40
1.65	- 70	- 82	-100	-27	- 31	- 35	- 40	- 42
2.0	- 60	- 72	- 89	-27	- 36	- 38	- 40	- 45
2.35	- 50	- 64	- 78	-22	- 41	- 43	- 51	- 52
2.85	- 38	- 49	- 70	-20	- 44	- 46	- 63	- 54
3.25	- 13	- 30	- 44	-20	- 49	- 53	- 59	- 61
3.65	+ 23	+ 13	+ 10	-17	- 58	- 61	- 67	- 70
4.0	+ 48	+ 38	+ 22	-14	- 60	- 66	- 72	- 74
4.55	+ 91	+ 85	+ 89	-14	- 73	- 78	- 83	- 83
4.9	+121	+114	+122	-13	- 78	- 82	- 90	- 94
5.25	+159	+152	+158	-12	- 84	- 91	-100	-105
5.65	+228	+221	+217	-11	- 99	-102	-111	-108
5.95	+309	+295	+283	- 9	-104	-111	-116	-119
6.3	+436	+422	+409	- 2	-117	-121	-129	-134
6.7	+677	+585	+466	+18	-130	-137	-146	-150
7.0	+750	+768	+748	+46	-150	-157	-165	-167
7.25								
8.25	failure							

i indicates before transfer

ii indicates after transfer

*NOTE: x 10^{-4} inches, (+ tension, - compression)

TABLE B.8.3

DEFLECTIONS

LOAD (kips)	NORTH * (in)	℄ (in)	SOUTH * (in)
0	0	0	0
.4	.03	.04	.03
.8	.07	.09	.07
1.25	.10	.13	.10
1.65	.13	.17	.14
2.0	.17	.21	.17
2.35	.21	.26	.21
2.85	.25	.32	.26
3.25	.31	.40	.32
3.65	.42	.54	.42
4.0	.50	.64	.50
4.55	.64	.82	.64
4.9	.74	.95	.74
5.25	.86	1.09	.86
5.65	.98	1.26	.99
5.95	1.12	1.43	1.12
6.3	1.31	1.68	1.31
6.7	1.56	2.03	1.56
7.0	1.80	2.36	1.80
7.25	2.20	2.91	2.19
7.5	2.58	3.46	2.57
7.75	3.11	4.21	3.11
8.0	4.23	5.81	4.23
8.25	-	6.86	-

* indicates 1/3 points

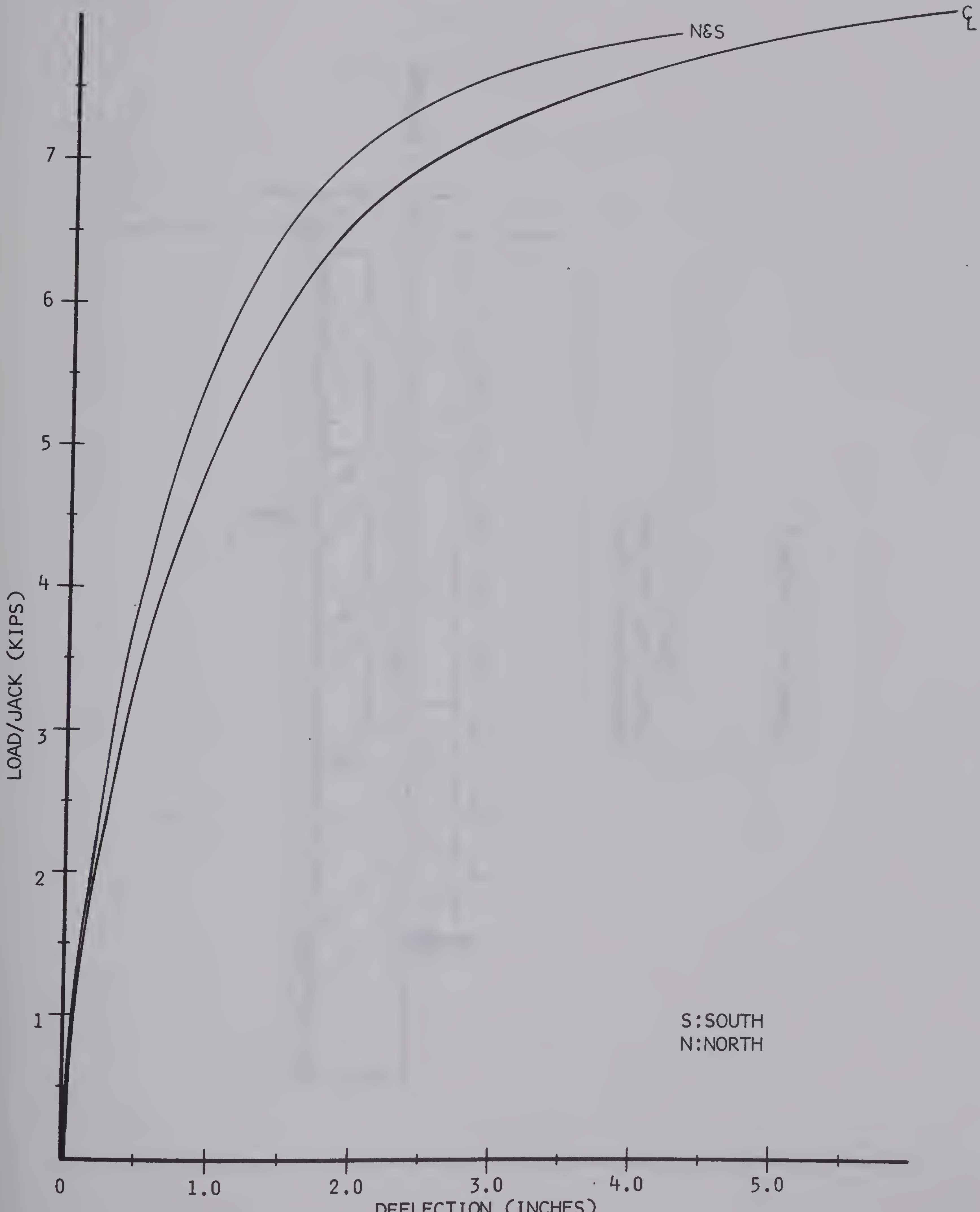
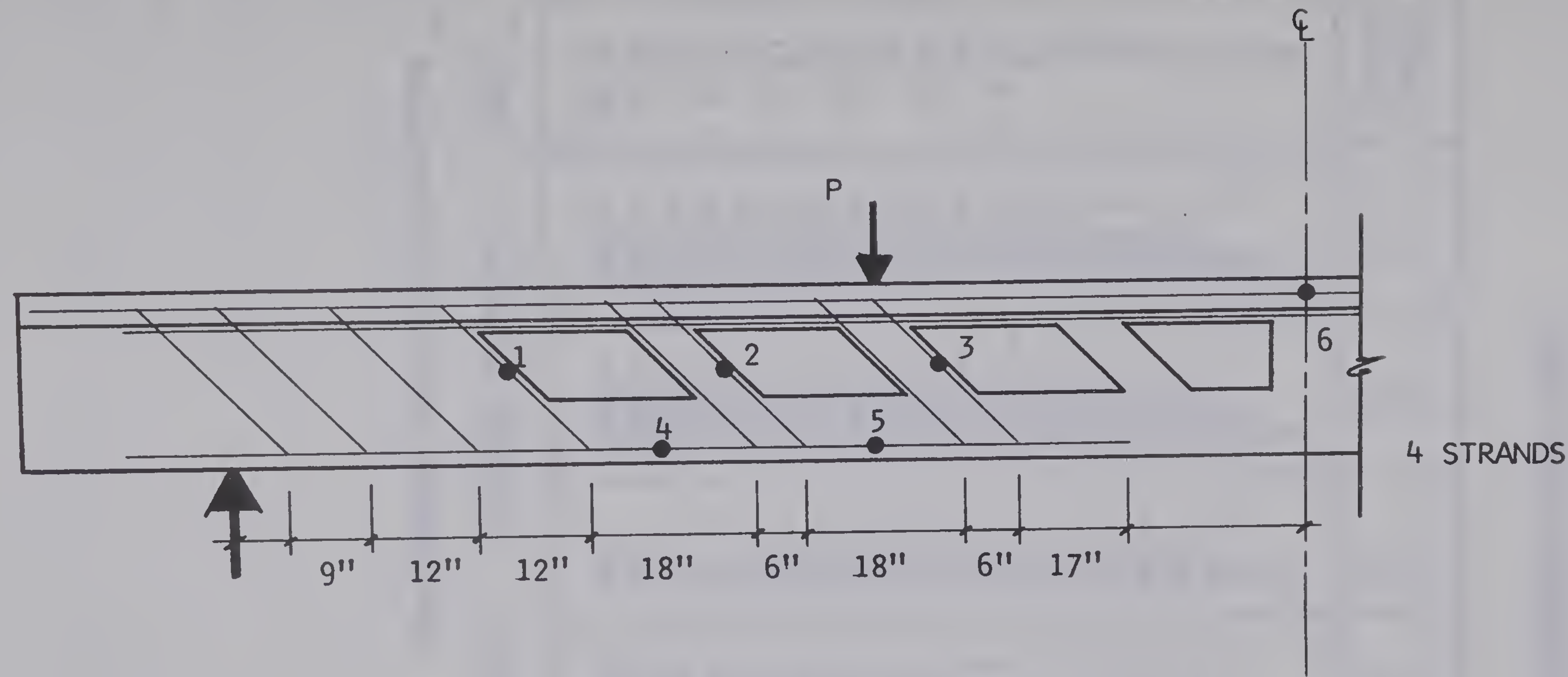


FIGURE B.8.2 LOAD-DEFLECTION DIAGRAM, BEAM 8



REINFORCEMENT DETAIL
STRAIN GAGE LOCATIONS
BEAM 9

FIGURE B.9.1 BEAM 9

TABLE B.9.1

STRAIN GAGE MEASUREMENTS

LOAD (kips)	(1) **	(2) **	(3) **	(4) **	(5) **	(6) **
0	0	0	0	0	0	N.A.
2	+ 30*	+ 50	+ 8	+ 42	+ 80	
4	+ 92	+ 229	+ 18	+ 100	+ 188	
6	+ 262	+ 568	+ 35	+ 161	+ 300	
8	+ 625	+ 784	+ 48	+ 210	+ 408	
10	+ 950	+1005	+ 34	+ 254	+ 710	
12	+1140	+1125	+ 31	+ 325	+1550	
13	+1235	+1168	+ 28	+ 393	+1830	
13.5	+1298	+1207	+ 62	+ 458	+2010	
14	+1354	+1230	+167	+ 663	+2200	
14.5	+1400	+1252	+151	+1040	+2360	
15	+1458	+1305	+138	+1156	+2500	
15.5	+1500	+1340	+118	+1325	+2690	
16	+1550	+1370	+ 85	+1476	+2890	
16.5	+1580	+1387	+ 60	+1580	+3030	
17	+1640	+1405	+ 29	+1700	+2860	
17.5	+1670	+1423	+ 13	+1780	+2890	
18	+1730	+1445	- 5	+1900	+3090	
18.5	+1800	+1480	- 50	+2000	+3180	
18.75	+1870	+1520	- 96	+2060	+3340	

* NOTE: + indicates tension; - indicates compression

** Measurements in micro inches/inch

TABLE B.9.2

DEMEC POINT MEASUREMENTS

LOAD (kips)	(1)	(2)	(3)	(5)	(6)	(7)	(8)	(9)
i	0	0	0	0	0	0	0	0
ii	- 48*	- 33	- 32	- 12	+ 9	+ 4	+ 1	+ 2
0	-116	- 99	- 90	- 46	- 26	- 21	- 24	- 21
2	-106	- 93	- 87	- 46	- 32	- 22	- 27	- 24
4	- 99	- 93	- 83	- 47	- 29	- 29	- 27	- 31
6	- 89	- 93	- 76	- 48	- 40	- 41	- 41	- 37
8	- 81	- 95	- 71	- 51	- 38	- 38	- 46	- 41
10	- 72	- 89	- 61	- 53	- 44	- 55	- 55	- 51
12	- 60	- 72	- 39	- 40	- 75	- 75	- 77	- 75
13	- 17	- 30	+ 2	- 31	- 82	- 88	- 72	- 84
13.25	- 6	- 16	+ 13	- 31	- 84	- 90	- 89	- 88
13.5	+ 8	- 4	+ 31	- 31	- 87	- 91	- 90	- 79
13.75	+ 21	+ 8	+ 42	- 34	- 90	- 91	- 93	- 93
14	+ 35	+ 20	+ 59	- 31	- 90	- 91	- 91	- 89
14.25	+ 44	+ 36	+ 80	- 26	- 90	- 93	- 94	- 95
14.5	+ 61	+ 53	+ 95	- 25	- 96	-101	- 89	- 94
14.75	+ 69	+ 60	+ 107	- 27	- 97	- 93	-101	- 96
15	+ 81	+ 78	+ 124	- 18	- 98	- 93	-101	- 98
15.5	+116	+109	+ 163	- 18	-104	- 97	-108	-108
16	+157	+151	+ 216	- 7	-111	-118	-101	-116
16.5	+196	+189	+ 272	+ 3	-107	-113	-122	-116
17	+144	+146	+ 243	+ 6	-119	-126	-123	-121
17.5	+191	+206	+ 315	+ 18	-122	-127	-125	-133
18	+263	+209	+ 360	+ 35	-137	-146	-146	-139
18.5	+274	+295	+ 441	+ 77	-164	-169	-159	-163
18.75	+790	+958	+1261	+108	-173	-175	-177	-176
20.25	failure							

i indicates before transfer

ii indicates after transfer

*NOTE: x 10^{-4} inches, (+ tension, - compression)

TABLE B.9.3

DEFLECTIONS

LOAD (kips)	SOUTH * (in)	℄ (in)	NORTH * (in)
0	0	0	0
2	.04	.03	.04
4	.09	.11	.09
6	.14	.16	.15
8	.20	.23	.20
10	.29	.33	.28
12	.56	.68	.56
13	.68	.83	.66
14	.84	1.02	.83
14.5	.91	1.12	.90
15	.96	1.20	.96
15.5	1.06	1.30	1.06
16	1.18	1.45	1.16
16.5	1.28	1.60	1.27
17	1.42	1.75	1.38
17.5	1.51	1.90	1.50
18	1.75	2.19	1.74
18.5	2.14	2.72	2.10
19	2.80	3.58	2.68
19.5	3.19	4.26	3.17
20	4.34	5.53	4.01
20.25	5.04	6.36	4.52

* indicates 1/3 points

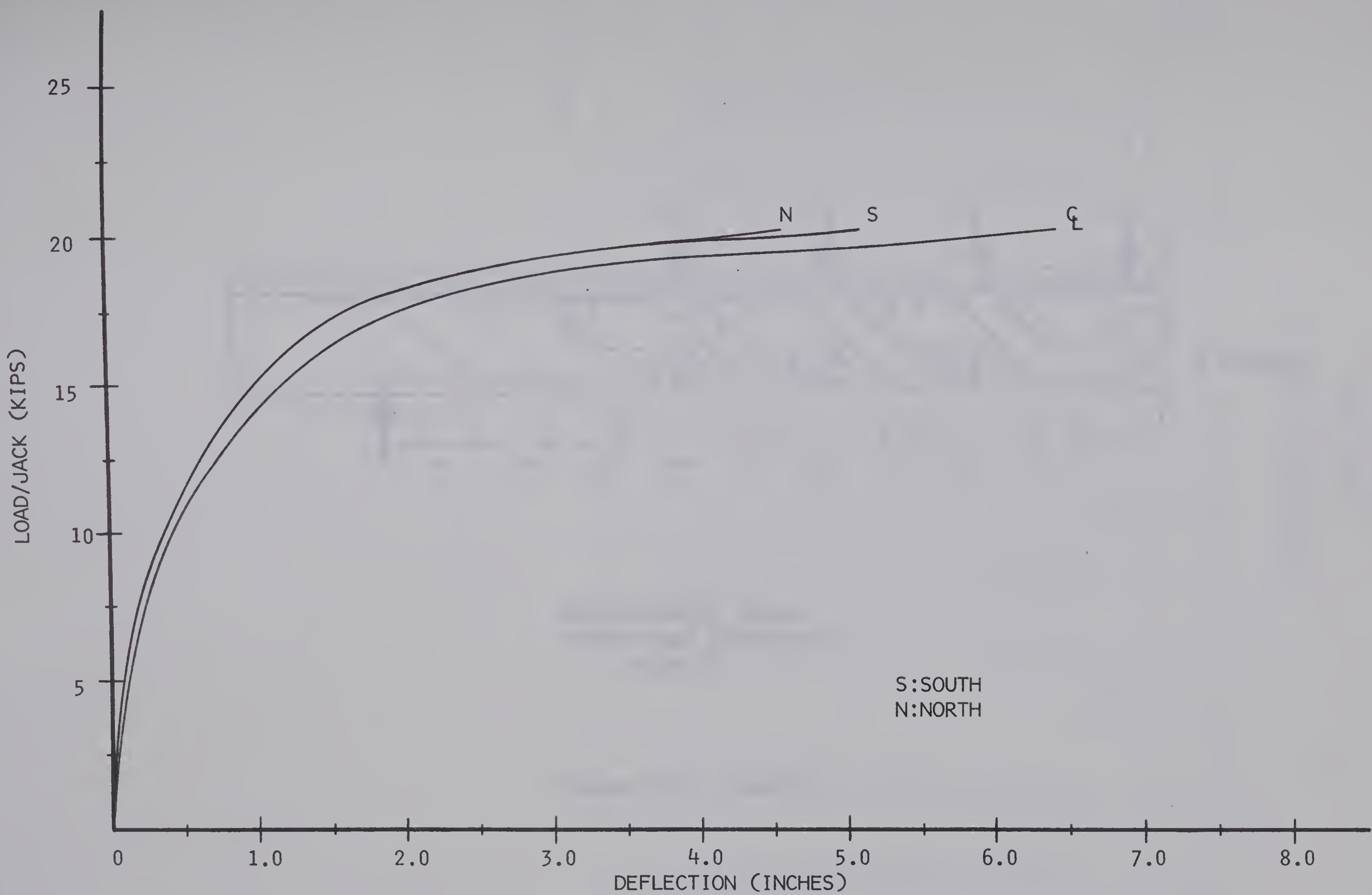
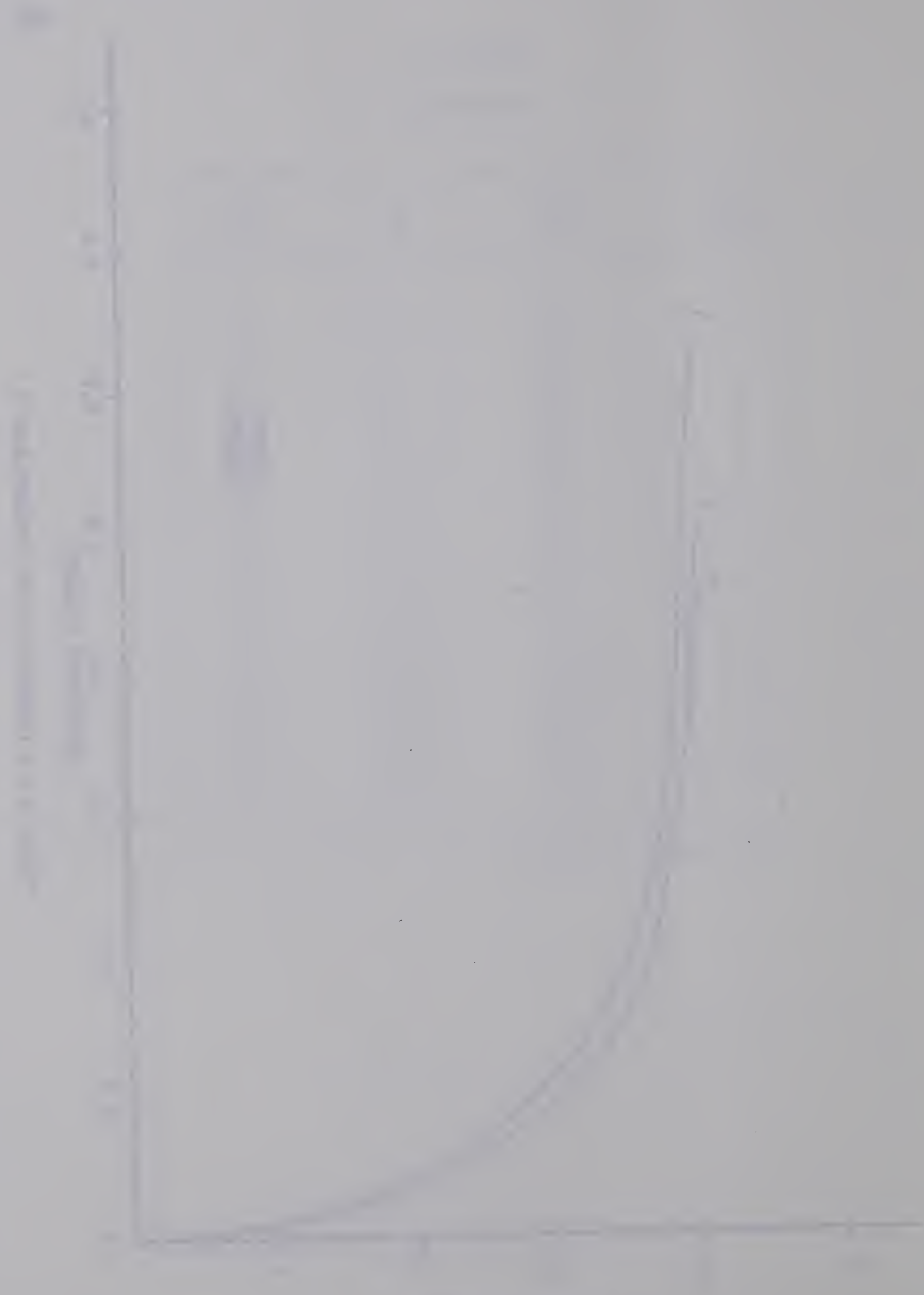
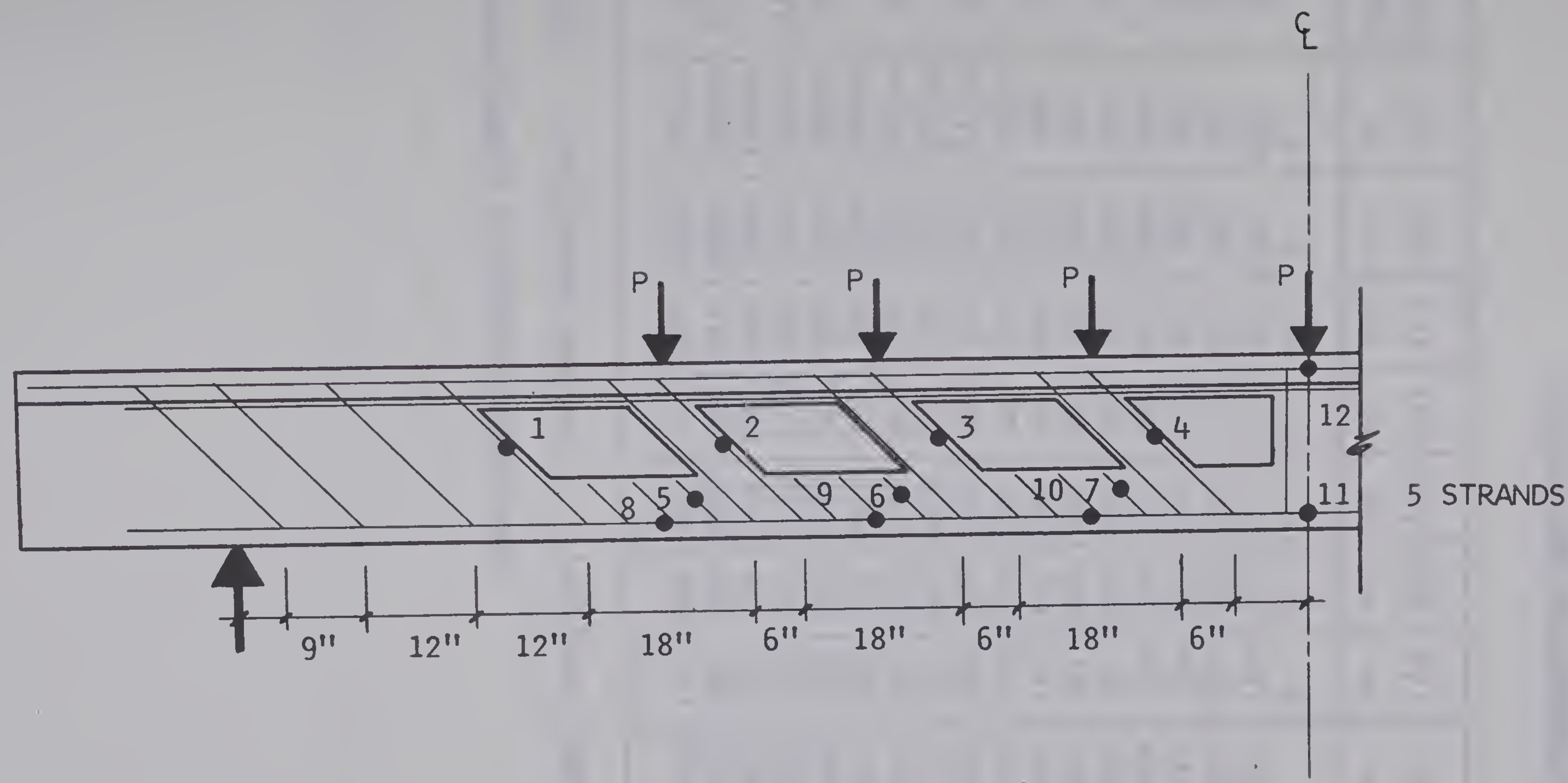


FIGURE B.9.2 LOAD-DEFLECTION DIAGRAM, BEAM 9





REINFORCEMENT DETAIL
STRAIN GAGE LOCATIONS
BEAM 10

FIGURE B.10.1 BEAM 10

TABLE B.10.1

STRAIN GAGE MEASUREMENTS

LOAD (kips)	(1) **	(2) **	(3) **	(4) **	(5) **	(6) **	(7) **	(8) **	(9) **	(10) **	(11) **	(12) **
0	0	0	0	0	0	0	0	0	0	N.A.	0	0
.5	+31*	+41	+26	+10	+12	+14	+17	+58	+77		+85	- 36
1.0	+57	+88	+54	+17	+19	+24	+30	+106	+141		+157	- 66
1.5	+107	+331	155	+31	+41	+45	+51	+175	+240		+265	-108
2	+350	+605	298	+40	+59	+70	+71	+240	+338		+372	-145
2.5	+540	+855	431	+46	+76	+98	100	+303	+453		+484	-181
3	+730	1015	488	+50	+90	140	137	+365	+575		+630	- 75
3.5	+890	1153	498	+42	160	257	317	+461	+841		+1220	-245
4	+1020	1290	492	+33	200	462	510	+573	1136		+1780	-274
4.5	+1170	1373	533	102	255	608	663	+830	1580		+2360	-298
5	+1353	1451	598	208	339	684	772	1129	2050		+2950	-324
5.5	+1500	1550	682	296	520	726	848	1400	2520		+3110	-340
6	+1660	1670	662	498	636	763	893	1700	3120		+6200	-346
6.5	+1850	1750	620	670	682	818	853	2000	3200		+8800	-344
6.75	+1920	1810	580	812	675	850	807	2220	3220		+10550	-325
7	+1950	1920	658	783	627	817	763	2380	3180			-288
7.25	+1950	1980	619	792	590	865	780	2550	3180			-213
7.5	+1950	2000	548	755	534	880	757	2730	3210			

* NOTE: + indicates tension; - indicates compression

** Measurements in micro inches/inch

TABLE B.10.2

DEMEC POINT MEASUREMENTS

LOAD (kips)	(1)	(2)	(3)	(5)	(6)	(7)	(8)	(9)
i	0	0	0	0	0	0	0	0
ii	- 64*	- 62	- 63	-26	+ 2	+ 8	- 3	- 5
0	- 116	- 111	-112	-45	- 33	- 27	- 29	- 36
0.5	- 107	- 106	-110	-47	- 39	- 31	- 36	- 41
1.0	- 97	- 98	-100	-47	- 36	- 33	- 39	- 39
1.5	- 92	- 94	- 99	-49	- 45	- 41	- 48	- 47
2.0	- 81	- 84	- 89	-53	- 52	- 51	- 52	- 49
2.5	- 76	- 76	- 84	-54	- 55	- 54	- 54	- 49
3.0	- 57	- 62	- 75	-58	- 58	- 57	- 64	- 62
3.5	+ 10	+ 1	- 21	-57	- 62	- 66	- 70	- 67
4.0	+ 64	+ 48	+ 24	-56	- 78	- 79	- 85	- 81
4.5	+ 123	+ 103	+ 74	-51	- 90	- 89	- 86	- 89
5.0	+ 183	+ 153	+117	-44	- 99	-100	-104	- 98
5.5	+ 250	+ 211	+168	-40	- 107	-110	-112	-111
6.0	+ 393	+ 310	+257	-26	- 121	-123	-129	-126
6.5	+ 535	+ 441	+281	-21	- 143	-142	-149	-145
6.75	+ 668	+ 560	+490	- 2	- 153	-153	-158	-154
7.0	+ 931	+ 794	+691	+24	-166	-179	-191	-187
7.25	+ 1328	+ 1123	+986	+64	194	-205	-227	-223
7.5	failure							

i indicates before transfer

ii indicates after transfer

*NOTE: x 10^{-4} inches, (+ tension, - compression)

TABLE B.10.3

DEFLECTIONS

LOAD (kips)	NORTH * (in)	℄ (in)	SOUTH * (in)
0	0	0	0
.5	.04	.05	.04
1.0	.08	.10	.08
1.5	.14	.16	.13
2.0	.19	.22	.17
2.5	.24	.28	.22
3.0	.29	.35	.28
3.5	.38	.45	.32
4.0	.51	.60	.41
4.5	.65	.78	.56
5.0	.81	.97	.70
5.5	.96	1.18	.88
6.0	1.20	1.48	1.10
6.5	1.45	1.83	1.39
6.75	1.70	2.13	1.58
7.0	2.02	2.58	1.93
7.25	2.42	3.09	2.26
7.5	-	3.85	-

* indicates 1/3 points

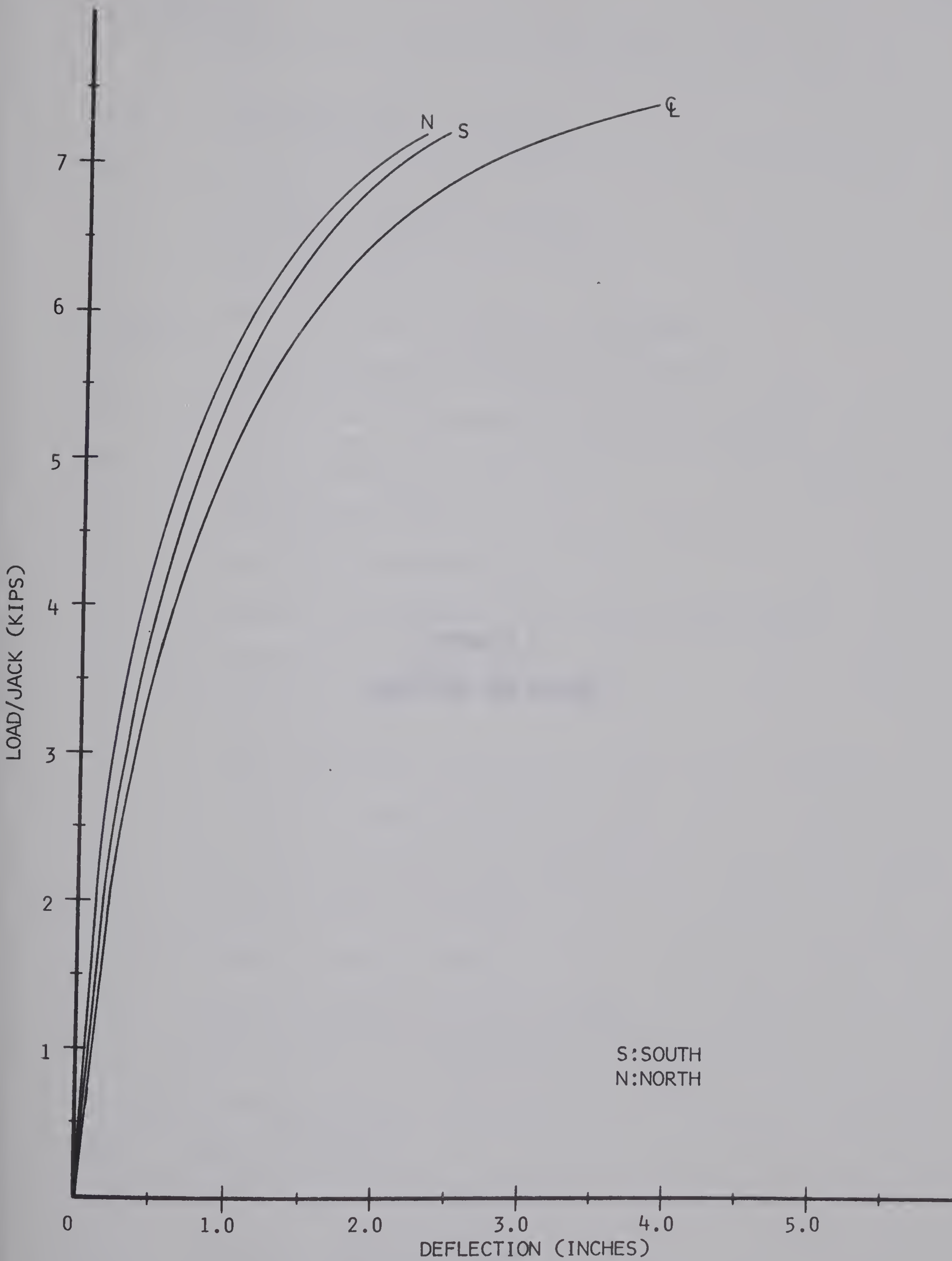


FIGURE B.10.2 LOAD-DEFLECTION DIAGRAM, BEAM 10

APPENDIX C
NOTATION AND DESIGN

C.1 Notation

A_{ct}	Transformed area of section
A_s	Area of prestressing steel
I_t	Transformed moment of inertia
M_c	Dead load moment
M_{TOTAL}	Dead load moment and applied load moment
f_c'	Ultimate compressive strength of concrete
f_s'	Ultimate tensile strength of prestressing steel
f_i	Initial prestress
f_e	Effective prestress
P	Prestress force (effective)
y	Distance from geometric centroid to extreme fiber
e	Eccentricity of prestressing steel
K_t	Upper kern point
K_b	Lower kern point
a	Position of neutral axis at failure
fsu	Calculated ultimate steel stress
P_i	Prestress force (initial)
d	Effective depth of member
b	Width of compression face of member
p	Ratio of steel to concrete area
s	Stirrup spacing
Av	Area of stirrup
fy	Yield stress of stirrup
Vu	Shear due to ultimate load

v_{cw} Shear stress at diagonal cracking, due to principal tension stress in the web

v_{ci} Shear stress at diagonal cracking, due to combined moment and shear

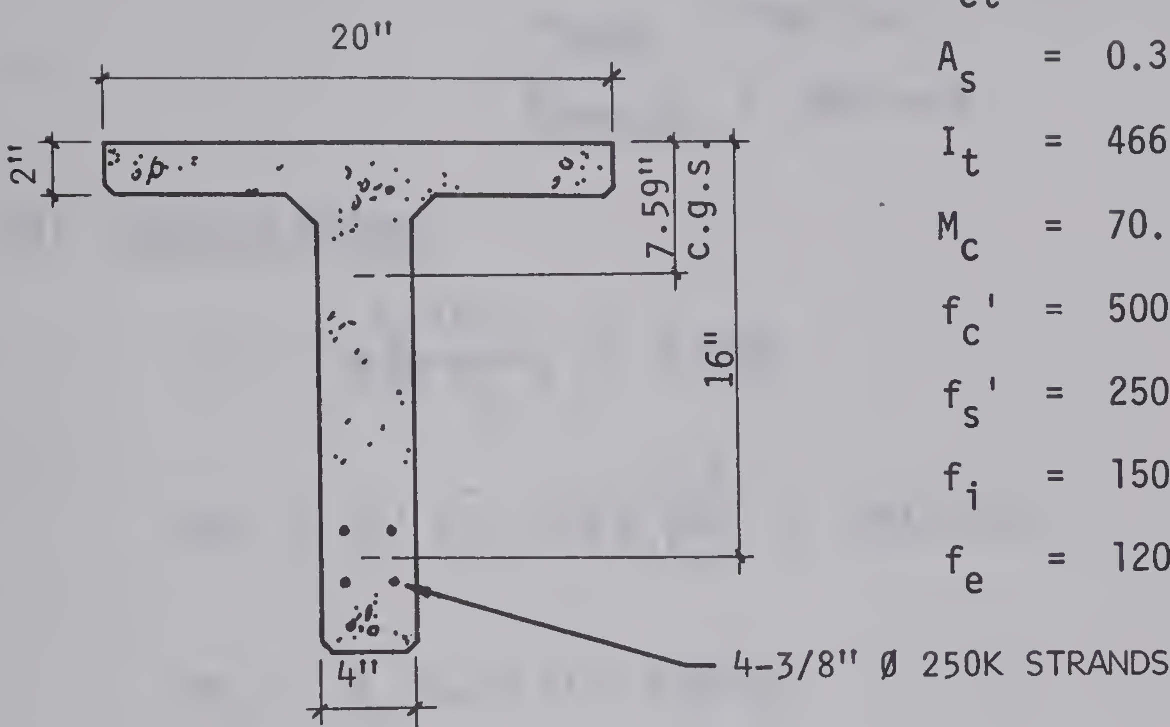
v_c Shear stress carried by concrete

C.2 Design

The shear design figures shown in this appendix, were obtained using the various formulae in the ACI 318-63 Code[1] and also the Proposed Revision of ACI 318-63 Code[2]. For the sections containing no openings, the shear stresses were calculated with a b'd of 64 in^2 and for those containing openings, with a b'd of 32 in^2. This was the only method used in the calculations to differentiate between the section with openings and that without openings.

The stirrup spacing, calculated for the section with openings, was not followed in the actual construction of the beams with openings, because the formulae are only applicable to solid sections. The spacing used for the shear stirrups, was determined by the experience of the author in designing for shear stresses and also from Sauve's[8] tests. The number of stirrups used per post in the beams with web openings was an equivalent number, determined by the stirrup spacing in the solid shear span.

4 STRAND SECTION DESIGN



A_{ct} = 113.9 in^2

A_s = 0.3196 in^2

I_t = 4664.3 in^4

M_c = 70.5 in-k

f_c' = 5000 psi

f_s' = 250 ksi

f_i = 150 ksi

f_e = 120 ksi

(1) Fiber Stresses at Transfer

Top at support: f_c = 235 psi tension

Top at ℄ : f_c = 120.5 psi tension

Bottom at ℄ : f_c = 1305 psi compression

(2) Kern Points

K_t = 3.26 in.

K_b = 5.34 in.

(3) Working Load Moment (for "0" stress at ℄ bottom fibers)

$$M_{TOTAL} = \frac{It}{Y}\left(\frac{P}{A_{ct}} + \frac{P \cdot e \cdot Y}{It}\right)$$

$$P_i = 150{,}000\ (0.3196) = 48{,}000 \text{ lb.}$$

$$P = 120{,}000\ (0.3196) = 38{,}400 \text{ lb.}$$

$$M_{TOTAL} = 450 \text{ in-k}$$

$$M_{APPLIED} = 380 \text{ in-k}$$

(4) Ultimate Moment

$$a = \frac{A_s \text{ fsu}}{0.85\, f_c'\, b} = 0.9165$$

$$\text{fsu} = f_s'\ (1 - 0.5\ p\ \frac{f_s'}{f_c'}) = 243.75 \text{ ksi}$$

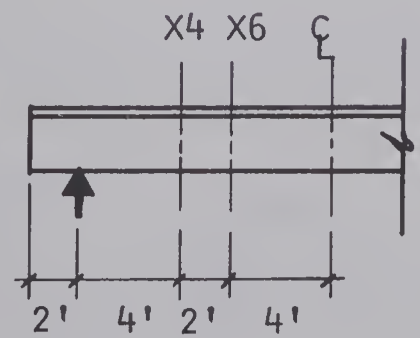
$$M_u = A_s \text{ fsu } d\ (1 - 0.59\ q)$$

$$q = \frac{p \text{ fsu}}{f_c'}$$

$$M_u = 1210 \text{ in-k}$$

$$M_{APPLIED} = 1140 \text{ in-k}$$

(5) Ultimate Shear



CRITICAL SECTIONS

Minimum Requirement:

$$s = \frac{Av \times 80 \times fy \times d}{A_s \times f_s'} = 77.5 \text{ in.}$$

Minimum Spacing (1963) = 3/4 x depth = 15 in
(Vertical Stirrups)

Calculations for shear reinforcing at the critical sections are shown in Table C.1.

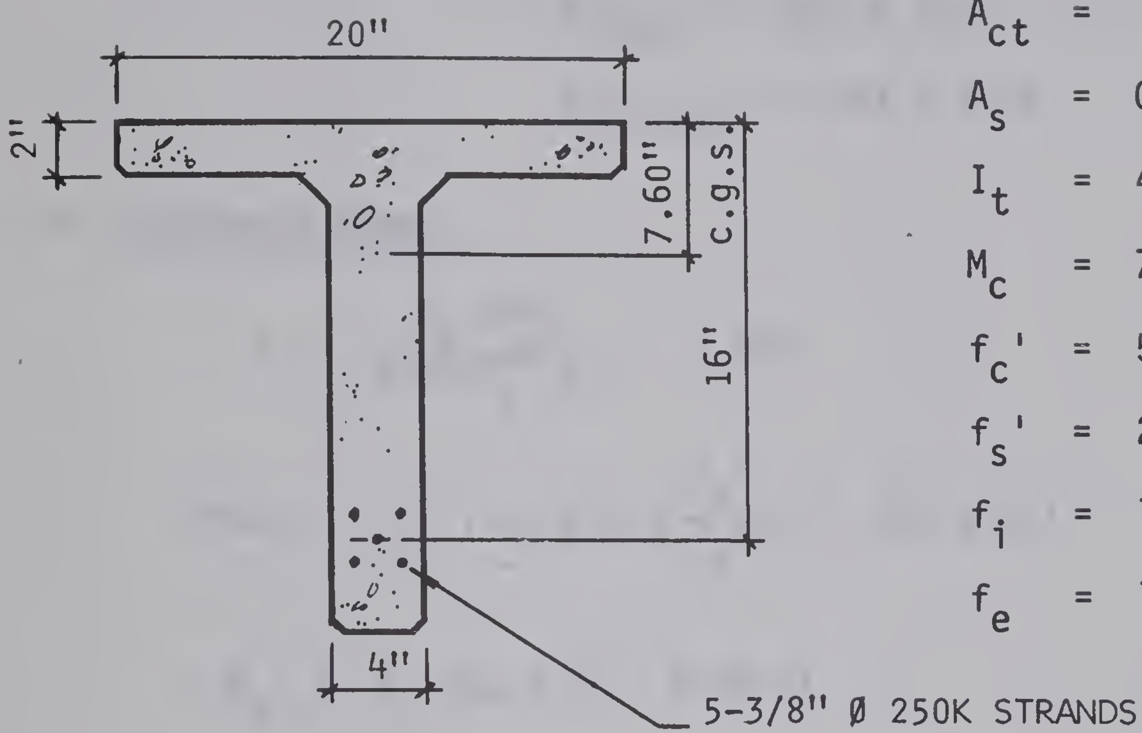
TABLE C.1

CALCULATIONS FOR SHEAR REINFORCEMENT - 4 STRAND BEAMS

LOADING	2 @ 12'c/c	2 @ 8'c/c	7 @ 2'c/c
Critical Section	X4	X6	X6
Dead Load Shear (k)	0.70	0.47	0.47
Dead Load Moment (in-k)	44.93	58.97	58.97
Cracking Moment (in-k)	566	552	552
v_{cw} (1963) (ksi)	0.350	0.350	0.350
v_{ci} (1963) (ksi)	0.271	0.184	0.153
v_c (1963) (ksi)	0.271	0.184	0.153
v_c (1971) (ksi)	0.276	0.198	0.165
Ultimate Shear	23.75	15.85	10.32
Stirrup Spacing			
Vertical Stirrups - No Holes			
s(1963) (in)	24.2	38.0	293
s(1971) (in)	25.2	48.7	-
s(v_c = 0) (in)	6.5	9.8	15.0
Inclined Stirrups - No Holes			
s(1963) (in)	34.2	53.7	414
s(1971) (in)	36.0	68.9	-
s(v_c = 0) (in)	9.2	13.8	21.2
Vertical Stirrups - Holes			
s(1963) (in)	5.1	7.8	14.3
s(1971) (in)	5.2	8.1	15.4
s(v_c = 0) (in)	3.3	4.9	7.5
Inclined Stirrups - Holes			
s(1963) (in)	7.3	11.0	20.2
s(1971) (in)	7.3	11.5	21.7
s(v_c = 0) (in)	4.6	6.9	10.6

$$s(1963 \ \& \ 1971) \ [\text{Vertical}] = \frac{2.42}{\left(\frac{V_u}{64} - v_c\right)} \qquad s(1971) \ [\text{Inclined}] = \frac{3.42}{\left(\frac{V_u}{64} - v_c\right)}$$

5 STRAND SECTION DESIGN



$A_{ct} = 114.4 \text{ in}^2$

$A_s = 0.3995 \text{ in}^2$

$I_t = 4701.3 \text{ in}^4$

$M_c = 70.5 \text{ in-k}$

$f_c' = 5000 \text{ psi}$

$f_s' = 250 \text{ ksi}$

$f_i = 150 \text{ ksi}$

$f_e = 120 \text{ ksi}$

(1) Fiber Stresses at Transfer

Top at support: $f_c = 289.9$ psi tension

Top at ℄ : $f_c = 175.9$ psi tension

Bottom at ℄ : $f_c = 1665.2$ psi compression

(2) Kern Points

$K_t = 3.31$ in.

$K_b = 5.40$ in.

(3) Working Load Moment (for "0" stress at ℄ bottom fibers)

$$M_{TOTAL} = \frac{It}{Y}\left(\frac{P}{A_{ct}} + \frac{P \cdot e \cdot Y}{It}\right)$$

$$Pi = 150{,}000\ (0.3995) = 59{,}925\ \text{lb.}$$

$$P = 120{,}000\ (0.3995) = 47{,}940\ \text{lb.}$$

$$M_{TOTAL} = 561.5\ \text{in-k}$$

$$M_{APPLIED} = 491.3\ \text{in-k}$$

(4) Ultimate Moment

$$a = \frac{A_s\ fsu}{0.85\ f_c'\ b} = 1.140$$

$$fsu = f_s'\ (1 - 0.5\ p\ \frac{f_s'}{f_c'}) = 242.5\ \text{ksi}$$

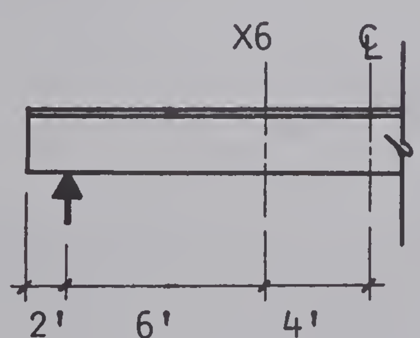
$$M_u = A_s\ fsu\ d\ (1 - 0.59\ q)$$

$$q = p\ \frac{fsu}{f_c'}$$

$$M_u = 1497.3\ \text{in-k}$$

$$M_{APPLIED} = 1427\ \text{in-k}$$

(5) Ultimate Shear



CRITICAL SECTION

Minimum Requirement:

$$s = \frac{Av \times 80 \times fy \times d}{A_s \times f_s} = 62.0\ \text{in.}$$

Minimum Spacing (1963) = 3/4 x depth = 15 in.
(Vertical Stirrups)

Calculations for shear reinforcing at the critical sections are shown in Table C.2.

TABLE C.2

CALCULATIONS FOR SHEAR REINFORCEMENT - 5 STRAND BEAMS

LOADING	2 @ 8'c/c	7 @ 2'c/c
Critical Section	X6	X6
Dead Load Shear (k)	0.47	0.47
Dead Load Moment (in-k)	58.97	58.97
Cracking Moment (in-k)	663.23	663.23
v_{cw} (1963) (ksi)	0.373	0.373
v_{ci} (1963) (ksi)	0.212	0.174
v_c (1963) (ksi)	0.212	0.174
v_c (1971) (ksi)	0.165	0.198
Ultimate Shear		
Stirrup Spacing		
Vertical Stirrups - No Holes		
s(1963) (in)	24.8	86.8
s(1971) (in)	21.7	65.6
s(v_c = 0) (in)	7.8	12.0
Inclined Stirrups - No Holes		
s(1963) (in)	35.0	122.7
s(1971) (in)	30.6	92.7
s(v_c = 0) (in)	11.0	16.9
Vertical Stirrups - Holes		
s(1963) (in)	5.9	10.5
s(1971) (in)	5.7	10.1
s(v_c = 0) (in)	3.9	6.0
Inclined Stirrups - Holes		
s(1963) (in)	8.4	14.9
s(1971) (in)	8.1	14.3
s(v_c = 0) (in)	5.5	8.5

s(1963 & 1971) [Vertical] $= \dfrac{2.42}{\left(\dfrac{V_u}{64} - v_c\right)}$ s(1971) [Inclined] $= \dfrac{3.42}{\left(\dfrac{V_u}{64} - v_c\right)}$